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Feasibility Study: Compilation and Evaluation of Properties Data for Basalt, Granite, Tuff, and Shale

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National Measurement Laboratory
U.S. Department of Commerce
National Bureau of Standards
Washington, DC 20234

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Final

Prepared for
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Battelle Memorial Institute
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

FEASIBILITY STUDY: COMPILATION AND EVALUATION OF PROPERTIES DATA FOR BASALT, GRANITE, TUFF, AND SHALE

Lewis H. Gevantman

A study on the feasibility of compiling and evaluating selected physical property data on basalt, granite, shale, and tuff has been completed. The data are to be used to design geological waste repositories for radioactive nuclear waste. Sufficient data on the thermodynamic, mechanical, thermophysical, and electrical properties have been identified to exist in the literature to warrant further data evaluative effort. A bibliography of the selected data is given.

Key Words: Basalt; bibliography; electrical properties; granite; mechanical properties; nuclear waste isolation; shale; thermodynamic properties; thermophysical properties; tuff.

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Purpose

This effort was initiated to determine the feasibility of assembling an evaluated numerical generic data base on the properties of selected geological materials. The selection of such materials is predicated on their utility as a medium in which to store highly radioactive nuclear waste. The materials of interest have been identified by the Office of Nuclear Waste Isolation (ONWI) and are salt, granite, basalt, tuff, and shale. A data base has been compiled on the properties of domed and bedded salt, and is contained in a monograph which will be issued soon [1]. Another compilation on salt, shale, basalt, and granite covering their geological, hydrological, and seismological properties was published recently [2]. However, the thermophysical, electrical and other properties for the latter three materials are not treated in sufficient depth to permit decisions to be made on the design of repositories in these media. Consequently a more detailed survey of the literature has been made to establish the extent and depth of coverage of data for these materials. The outcome of this effort will be used to judge the value of proceeding with the evaluation of the data to form a data base for use in waste repository design.

Approach

The National Bureau of Standards' Office of Standard Reference Data (NBS-OSRD) was given the task of assembling a body of experts to perform this task. It turned to two data centers: the National Center for the Thermodynamic Data of Minerals, under the direction of Dr. John L. Haas, Jr., and the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) under the direction of Professor Y. S. Touloukian. The former is located at the U. S. Geological Survey, Reston, Virginia, and the latter at Purdue University, West Lafayette, Indiana. The material property data were assembled under the general headings of thermodynamic, mechanical, thermophysical, and electrical data. These in turn were further categorized into the chemical composition, mineralogy, heat capacity, enthalpy, entropy, Gibbs free energy, molar volume changes with pressure and temperature; elastic, dynamic, and static properties; compressive, tensile, and shear strength; creep; permeability, porosity, and hardness; thermal conductivity, expansion, capacity, and diffusivity; electrical conductivity as a function of selected parameters.

A complete bibliography was assembled and examined for data content. In addition, some review was given to the validity of the data, both in terms of the proper application of the experimental measurement and the subsequent theoretical treatment to arrive at the desired value. A recommendation on whether to proceed with further effort could then be based upon a positive assessment of the existing data base.

Results

The results are detailed in two appendices. Each appendix represents the contribution of each data center in its area of expertise. Each appendix presents a bibliography, a sample of the data surveyed, the degree of reliance to be placed on the data, a review of the experimental techniques employed, and a recommendation on how to proceed beyond the present effort.

The results are summarized here to give an overall view of the degree of success achieved. Thus, in the area of thermodynamic property data it was established that sufficient data exist in the literature to characterize approximately 66 mineral phases common to granite, tuff, shale, and basalt. Where experimental data are lacking or insufficient, the properties will be estimated to an acceptable accuracy (< 5%). Difficulties in data evaluation are foreseen for mineral phases having variable water content and composition. As an example, Table 2 of Appendix 1 displays the available epxerimental data on the thermodynamic properties of minerals and is reproduced below. A more detailed reading of the available data is given in Table 3 of that appendix.

For mechanical property data it has been possible to identify over 200 out of 1100 papers surveyed which contain useful information. A series of tables has been constructed in Appendix 2 showing the density and elastic property data for the four materials of interest. In addition, graphs are plotted for selected material specimens to show the broad variation in reported value as a function of temperature or pressure. The data for permeability, porosity, and hardness are treated in similar fashion. Few data on hardness exist other than for granite.

Thermophysical and electrical property data have been culled and compiled from the literature. Ninety useful papers for thermophysical properties and 31 references for electrical properties have been assembled in Appendix 2. In addition, brief discussions on the applicability of selected experimental techniques are given.

Some examples for four thermophysical properties are presented for the four materials as a function of temperature. The data are presented graphically and show disparity in the reported values. Consequently many of the graphs are represented as a band of values rather than a single line.

The electrical properties discussed pertain mainly to conductivity and resistivity. Again the experimental techniques are discussed briefly, and then a few graphs and one table are included to demonstrate the type of data encountered. It is demonstrated that the electrical behavior of basalt and granite is dependent largely on water content. Little information exists on the electrical properties of shale and tuff.

Conclusions

As a result of the review of the literature and the preliminary examination of the data it is possible to conclude:

1. An adequate body of data exists for attempting an evaluative effort.
2. The data for thermodynamic properties either exist or can be estimated to provide a reliable data base.
3. The number of data values for mechanical, thermophysical, and electrical properties reported are adequate to narrow the choices required in the design criteria for nuclear waste repositories, but cannot be said to be of sufficient quality to permit recommended values. The utility of the evaluative process will be twofold: first, to narrow the spread between values, and second, to indicate where useful measurements can be made to improve data accuracy.
4. The electrical properties of shale and tuff are not well reported in the literature. Considerably more experimental data are required.
5. Site-specific data on all the properties seem lacking in varying degrees.
6. The generation of a generic data base for the properties and materials cited is timely because it provides a useful data base for present design criteria and points the direction for future data collection effort required to characterize a nuclear waste repository.

References

1. Gevantman, L. H., Editor, Physical Properties Data for Rock Salt, NBS Monograph 167, Washington, DC 1981.

2. Isherwood, Dana, Geoscience Data Base Handbook for Modeling a Nuclear Waste Repository, Vols. 1 and 2, prepared for U. S. Nuclear Regulatory Commission, NUREG/CR-0912, UCRL-52719, NRC FIN No. A0277, Washington, DC, 1980.

Feasibility Study
Data for Nuclear Waste Disposal, Thermodynamic Properties of Basalt, Granite, Shale, and Tuff

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Feasibility Study

Data for Nuclear Waste Disposal, Thermodynamic Properties of Basalt, Granite, Shale, and Tuff

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A compilation is presented of the available experimental data on the thermodynamic properties of 66 mineral phases which are commonly present in some of the rock types proposed as nuclear waste storage candidates: 1) granite, 2) tuff, 3) shale, and 4) basalt. A summary of the chemistry and mineralogy of each rock type is given. A procedure to evaluate an internally consistent set of thermodynamic properties for minerals from the compiled experimental data is presented.

It is concluded that sufficient data of quality exist to evaluate the thermodynamic properties of most of these mineral phases. These data are summarized in Table 2 and cited in detail in Table 3. Efforts will be focused on deriving the properties of the end-member components of mineral phases which possess solid solution. Where experimental data are lacking or insufficient, the properties of heat capacity, volume thermal expansion, and volume compressibility can be estimated with an accuracy of a few percent. The greatest uncertainties and evaluation difficulties are foreseen for mineral phases having variable water content (zeolites, some mineral hydrates, some clays).

Key words: Thermodynamics; minerals; nuclear waste; data evaluation.

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1. Introduction

The thermal and chemical environment of a potential nuclear waste repository must be known and understood before an intelligent decision can be made regarding radioactive waste storage. A properly evaluated set of thermodynamic data can provide some of the needed information. This report presents a procedure to evaluate an internally consistent set of thermodynamic data for minerals and contains a tabulation of experimental data which may be used in this evaluation. Experimental data pertinent to mineral phases in 1) granitic, 2) tuffaceous, 3) shale, and 4) basaltic rock types are presented.

The report is divided into two sections. The first section briefly summarizes the chemical and physical character of the proposed repository rock types and identifies for each rock type:

1. a generalized chemical system describing the rock type,
2. the major mineral constituents,
3. the minor mineral constituents, and
4. the common alteration phases.

The second section is in essence a tabular summary of all available experimental data on heat capacity, relative enthalpy, entropy, enthalpy of formation, enthalpy of reaction, Gibbs energy of reaction, chemical potential, molar volume, volume expansivity, and volume compressibility for the mineral phases of interest.

The data are to be used to generate an evaluated set of thermodynamic data for minerals. The evaluation will involve additional information for phases not tabulated here to provide an extensive, internally consistent, and hopefully reliable data base. An important feature of the evaluation procedure is the identification of inconsistent and erroneous data in the set of experimental data under consideration.

2. Summary of rock-type chemistry and mineralogy

2.1. Granite and other crystalline igneous rocks

Granitic crystalline igneous rocks occur as large, relatively homogeneous bodies which consist primarily of a granular aggregate of feldspar minerals and quartz. Grain size typically ranges between 1 mm to a few cm. The model chemical system is Na_2O-K_2O-CaO-(FeO)-(Fe_2O_3)-Al_2O_3-SiO_2-H_2O. Oxide components in parenthesis are of lesser importance. The minerals and their chemical formulas are given below. A typical analysis, including the norm and mode, is given on Table 1.

a. Major mineral constituents

The major minerals, as cited above are quartz and the feldspars. They generally account for up to 95 percent of the mineral volume. The formulas are as follows:

Quartz - SiO_2

Plagioclase feldspar - approximately Ano 20:Alb 80[1]

Albite - $NaAlSi_3O_8$

Anorthite - $CaAl_2Si_2O_8$

K-feldspar (microcline) - $KAlSi_3O_8$

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[1] Ano 20:Alb 80 signifies a composition of 20 percent anorthite and 80 percent albite of GFW (molar) units in the feldspar. The three-character abbreviations for end-member mineral components are defined in Table 4, p. 116. This notation style is used throughout the description of rock types.

b. Minor mineral constituents

The minor constituents of granites account for less than 5 volume percent of the rock and include the following:

Muscovite - $KAl_3Si_3O_{10}(OH)_2$
Biotite - commonly annite
    Annite - $KFe_3AlSi_3O_{10}(OH)_2$
    Phlogophite - $KMg_3AlSi_3O_{10}(OH)_2$
Garnet - commonly almandine
    Almandine - $Fe_3Al_2Si_3O_{12}$
Magnetite - Fe_3O_4
Amphibole - commonly hornblende - $Na_xCa_2(Mg,Fe)_{5-2y}$
$Al_{x+4y}Si_{8-x-2y}O_{22}(OH)_2$
$x \approx 0\text{-}1,\ y \approx 0.5$

c. Alteration phases

Alteration generally occurs near fractures at depth or near the weathering surface during erosion. Rock bodies which have experienced thermal metamorphism may show pervasive alteration. Alteration phases, besides quartz and the feldspars, include the following minerals:

- Epidote - Zoisite - $Ca_2FeAl_2Si_3O_{12}(OH)$ - $CaAl_3Si_3O_{12}(OH)$
- Clays
  - Kaolinite - $Al_2Si_2O_5(OH)_4$
  - Smectite - commonly montmorillonite - beidellite
    - Alkali-free
      - Montmorillonite - $Al_2Si_4O_{10}(OH)_2 \cdot nH_2O$
    - Montmorillonite - $(1/2Ca,Na)_{0.33}(Al_{1.67},(Mg,Fe)_{0.33}$ $Si_4O_{10}(OH)_2 \cdot nH_2O$
    - Beidellite - $(1/2Ca,Na)_{0.33}(Al_2)(Al_{0.33},Si_{3.67})$ $O_{10}(OH)_2 \cdot nH_2O$
    - Nontronite - $(1/2Ca,Na)_{0.33}(Fe^{+3})(Al_{0.33},Si_{3.67})$ $O_{10}(OH)_2 \cdot nH_2O$

      $n < 2$
- Calcite - $CaCO_3$

2.2. Tuff

Tuff is an indurated (hardened by temperature, pressure, and/or chemical reaction) volcanic deposit, predominantly composed of volcanic ash (fragmental volcanic material with a grain size diameter less than 4mm). The fragmental material may consist of:

1. quenched magma in the form of glass particles,
2. phenocrysts (crystals grown in the magma chamber), and
3. rock fragments.

Tuff occurs as sheetlike bodies surrounding volcanic centers, and deposits range from less than a meter to more than 1000 meters thick. Large tuff units commonly are formed from volcanic air-fall or avalanche deposits. The avalanche deposits may be welded from the heat present during deposition.

The bulk composition of large tuff sheets typically ranges between quartz latite-dacite and rhyolite. A representative analysis, norm, and mode are given in Table 1. The typical range of silica content and phenocrysts in large tuff sheets is as follows:

Rhyolite ←----→ Quartz Latite-Dacite
75 wt. % SiO_2 ←----→ 62 wt. % SiO_2
0% phenocrysts ←----→ 50% phenocrysts
(volume percent)

Tuffs can be categorized into several types, which occur as zones in large deposits (Smith, 1961, USGS Prof. Paper 354-F, 149-159, plate 20-D):

1. unwelded to partially welded zone
2. partially to completely welded zone

3. devitrified zone

4. altered zone

The model chemical system is $Na_2O-K_2O-CaO-(MgO)-(FeO)-(Fe_2O_3)-Al_2O_3-SiO_2-H_2O$. Mineral constituents of tuffs consist of phenocryst and matrix phases.

a. Phenocrysts

The phenocrysts which typically vary between 0 and 50 volume percent could be any one or more of the following:

Plagioclase feldspar - typically Ano 20:Alb 80 - Ano 50:Alb 50
  Albite - $NaAlSi_3O_8$
  Anorthite - $CaAl_2Si_2O_8$
K-feldspar (sanidine) - $KAlSi_3O_8$
Quartz - SiO_2
Biotite - typically annite
  Annite - $KFe_3AlSi_3O_{10}(OH)_2$
  Phlogophite - $KMg_3AlSi_3O_{10}(OH)_2$

b. Accessory phenocrysts

The accessory phenocrysts, which are typically less than 2 volume percent, may be one or more of the following:

Clinopyroxene - typically Ferroaugite - approximately
Hed 41:Dio 27:Cts 19:Cen 13
  Hedenbergite - $CaFe(SiO_3)_2$
  Diopside - $CaMg(SiO_3)_2$
  Ca-Al Clinopyroxene- $CaAl_2SiO_6$
  Clinoenstatite - $MgSiO_3$

Clinoferrosilite - $FeSiO_3$

Orthopyroxene

Enstatite - $MgSiO_3$

Ferrosilite - $FeSiO_3$

Wollastonite - $CaSiO_3$

Amphibole - commonly hornblende - $Na_xCa_2(Mg,Fe)_{5-2y}Al_{x+4y}Si_{8-x-2y}O_{22}(OH)_2$

$x \approx 0\text{-}1,\ y \approx 0.5$

Fayalite - Fe_2SiO_4

Magnetite - Fe_3O_4

Ilmenite - $FeTiO_3$

c. Matrix

Typically the matrix varies from about 50 to 100 volume percent. It varies by zone:

1. In the unwelded-to-partially-welded zone and the partially-welded-to-completely-welded zone, the typical matrix is glass or glass plus alteration products. Glass tends to hydrate with time. Unhydrated fresh glass typically has a water content of < 1 wt. percent H_2O, while hydrated glass typically has a water content of 2-4 percent. Porosity may range up to 50 percent in the unwelded-to-partially-welded zone.

2. In the devitrified zone the typical matrix is a microcrystalline intergrowth of alkali feldspar (Na-K feldspar) and cristobalite (SiO_2).

3. In the altered zone the matrix is typically clay (montmorillonite) and/or zeolite minerals replacing glass and sometimes phenocrysts.

Alteration occurs more rapidly in hydrated glass than unhydrated glass and hydration may be necessary to achieve alteration.

d. Alteration products

Typical alteration products are:

1. Clays
   - a. Smectite - commonly montmorillonite - beidellite

     Alkali-free montmorillonite - $Al_2Si_4O_{10}(OH)_2 \cdot nH_2O$

     Montmorillonite - $(1/2Ca,Na)_{0.33}(Al_{1.67},(Mg,Fe)_{0.33})Si_4O_{10}(OH)_2 \cdot nH_2O$

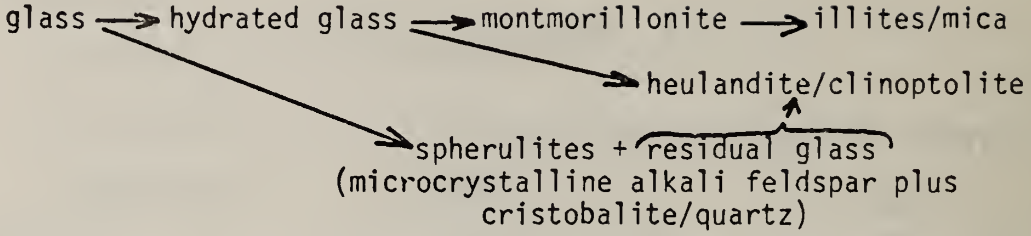
     Beidellite - $(1/2Ca,Na)_{0.33}(Al_2)(Al_{0.33},Si_{3.67})O_{10}(OH)_2 \cdot nH_2O$

     Nontronite - $(1/2Ca,Na)_{0.33}(Fe_2^{+3})(Al_{0.33},Si_{3.67})O_{10}(OH)_2 \cdot nH_2O$

     $n < 2$
   - b. Kaolinite/Halloysite/Dickite - $Al_2Si_2O_5(OH)_4$
2. Zeolites
   - a. Clinoptolite - $(Na,K,Ca)_{2-3}Al_3(Al,Si)_2Si_{13}O_{36} \cdot 12H_2O$

     (generally an impure heulandite)
   - b. Heulandite - $CaAl_2Si_7O_{18} \cdot 6H_2O$
   - c. Analcite - $NaAlSi_2O_6 \cdot H_2O$
3. Miscellaneous
   - a. Calcite - $CaCO_3$
   - b. Illite - $(K,H_3O)_{x+y}(Al_{2-x}(Mg,Fe)_x)(Si_{4-y},Al_y)O_{10}(OH)_2 \cdot 1\text{-}x\text{-}y\text{-}zH_2O$ $\quad x+y+z < 1$

Observed alteration sequences are[2]:



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[2] Barrows, 1980, GSA Bull., 91, 199-210.

2.3. Flood basalt

Flood basalt occurs as sheets of rapidly cooled basaltic lava erupted from a volcanic center in continental basement. Individual sheets typically have great areal extent and range between less than 1 meter to 100 meters in thickness.

The model chemical system is $CaO-(Na_2O)-FeO-(Fe_2O_3)-MgO-Al_2O_3-SiO_2-(H_2O,CO_2)$. A typical analysis, norm, and mode is given on Table 1.

a. Major constituents

The major constituents consist of phenocrysts and matrix phases. Phenocrysts typically account for 0 to 10 percent of the rock volume with matrix comprising the remainder. Gas bubbles (vesicles) occur in some basalt units, usually near the top surface of the flow.

1. Phenocrysts usually are:

Olivine - typically For 90:Fay 10
    Forsterite - Mg_2SiO_4
    Fayalite - Fe_2SiO_4
Plagioclase - typically Ano 60:Alb 40
    Anorthite - $CaAl_2Si_2O_8$
    Albite - $NaAlSi_3O_8$

2. Matrix, which typically is a microcrystalline intergrowth of:

Clinopyroxene - typically pigeonite - approximately Cen 46:Cfs 38:Dio 9:Hed 7
    Diopside - $CaMg(SiO_3)_2$
    Hedenbergite - $CaFe(SiO_3)_2$

Clinoenstatite - $MgSiO_3$
Clinoferrosilite - $FeSiO_3$
Hypersthene - approximately Ens 60:Fes 40
Enstatite - $MgSiO_3$
Ferrosilite - $FeSiO_3$
Plagioclase
Anorthite - $CaAl_2Si_2O_8$
Albite - $NaAlSi_3O_8$

b. Alteration products

Alteration products typically occur in vesicles or along fractures and flow-unit contacts in basalts. The low- and intermediate-temperature alterations are temperature-induced responses to heated fluids moving through the rock, and most of the alteration phases require the addition of either water or carbon dioxide to the rock. The intermediate- and high-temperature alterations are a result of thermal metamorphism of the rock body. Basalts which have experienced thermal metamorphism may show pervasive alteration.

1. Low temperature ($T < 250°C$) reactions typically produce the following minerals:

Calcite - $CaCO_3$
Dolomite - $CaMg(CO_3)_2$
Epidote - Zoisite - $Ca_2FeAl_2Si_3O_{12}(OH)$ - $Ca_2Al_3Si_3O_{12}(OH)$
Prehnite - $Ca_2Al_2Si_3O_{10}(OH)_2$
Lawsonite - $CaAl_2Si_2O_7(OH)_2 \cdot H_2O$

Zeolites

Laumontite - $CaAl_2Si_4O_{12} \cdot 4H_2O$

Heulandite - $CaAl_2Si_7O_{18} \cdot 6H_2O$

Analcite - $NaAlSi_2O_6 \cdot H_2O$

Wairakite - $CaAl_2Si_4O_{12} \cdot 2H_2O$

2. Intermediate temperature (T < 375°C) reactions typically produce the following minerals:

Calcite - $CaCO_3$

Dolomite - $CaMg(CO_3)_2$

Albite - $NaAlSi_3O_8$

Zoisite - $Ca_2Al_3Si_3O_{12}(OH)$

Chlorite (Clinochlore) - $Mg_5Al_2Si_3O_{10}(OH)_4$

Amphibole

Tremolite - $Ca_2Mg_5Si_8O_{22}(OH)_2$

Actinolite - $Ca_2Fe_5Si_8O_{22}(OH)_2$

Anthophyllite - $Mg_7Si_8O_{22}(OH)_2$

3. High temperature (T > 350°C) reactions typically produce the following minerals:

Amphibole - commonly Hornblende - $Na_xCa_2(Mg,Fe)_{5-2y}$

$Al_{x+4y}Si_{8-x-2y}O_{22}(OH)_2$

$x \approx 0\text{-}1,\ y \approx 0.5$

Garnet - typically Almandine or Grossular

Grossular - $Ca_3Al_2Si_3O_{12}$

- Almandine - $Fe_3Al_2Si_3O_{12}$
- Pyrope - $Mg_3Al_2Si_3O_{12}$

Clinopyroxene

- Hedenbergite - $CaFe(SiO_3)_2$
- Diopside - $CaMg(SiO_3)_2$
- Ca-Al Clinopyroxene - $CaAl_2SiO_6$
- Wollastonite - $CaSiO_3$

Orthopyroxene

- Enstatite - $MgSiO_3$
- Ferrosilite - $FeSiO_3$

Olivine

- Forsterite - Mg_2SiO_4
- Fayalite - Fe_2SiO_4

Spinel

- Magnetite - Fe_3O_4

2.4. Shale

Shale is a rock composed of detrital particles with an average grain-size diameter less than 1/16 mm in which the clay fraction (grainsize < 1/256 mm) predominates over the silt fraction (grainsize 1/16 - 1/256 mm). Detrital particles are fragmental material produced by the disintegration and weathering of rocks. Shales are an abundant rock type deposited in sedimentary basins and typically occur as tabular bodies with great areal extent.

The model chemical system is K_2O-MgO-(FeO)-(Fe_2O_3)-(Na_2O)-Al_2O_3-SiO_2-H_2O. A typical analysis and mode are given in Table 1.

a. Major constituents

The major constituents are as follows:

1. Clays
   a. Smectite - commonly montmorillonite - beidellite

      Alkali-free montmorillonite - $Al_2Si_4O_{10}(OH)_2 \cdot nH_2O$

      Montmorillonite - $(1/2Ca,Na)_{0.33}(Al_{1.67},(Mg,Fe)_{0.33})Si_4O_{10}(OH)_2 \cdot nH_2O$

      Beidellite - $(1/2Ca,Na)_{0.33}(Al_2)(Al_{0.33},Si_{3.67})O_{10}(OH)_2 \cdot nH_2O$

      Nontronite - $(1/2Ca,Na)_{0.33}(Fe_2^{+3})(Al_{0.33},Si_{3.67})O_{10}(OH)_2 \cdot nH_2O$

      $n < 2$

   b. Kaolinite/Halloysite/Dickite - $Al_2Si_2O_5(OH)_4$

   c. Illite - $(K,H_3O)_{x+y}(Al_{2-x},(Mg,Fe)_x)(Si_{4-y},Al_y)O_{10}(OH)_2 \cdot 1-x-y-zH_2O$ $x+y+z < 1$

   d. Mixed-layer clay - interlayered mixture of illite - smectite

2. Muscovite - $KAl_3Si_3O_{10}(OH)_2$

3. Chlorite

   Clinochlore - $Mg_5Al_2Si_3O_{10}(OH)_4$

4. Quartz - SiO_2

b. Typical minor constituents

Typical minor constituents are as follows:

1. Plagioclase - typically Ano 0:Alb 100 - Ano 5:Alb 95

   Albite - $NaAlSi_3O_8$

   Anorthite - $CaAl_2Si_2O_8$

2. K-feldspar (Microcline) - $KAlSi_3O_8$

3. Carbonates

   Calcite - $CaCO_3$

   Dolomite - $CaMg(CO_3)_2$

   Ankerite - $CaFe(CO_3)_2$

4. Oxides

   Magnetite - Fe_3O_4

   Hematite - Fe_2O_3

5. Organic matter

   Carbon - C

6. Pyrite - FeS_2

Table 1. Representative rock compositions

Oxide wt. %	Granite[a]	Tuff[b]	Basalt[c]	Shale[d]
Chemical composition				
SiO_2	73.60	66.0	53.8	58.10
TiO_2	0.18	0.55	2.0	0.65
Al_2O_3	13.84	15.4	13.9	15.40
Fe_2O_3	0.63	2.6	2.6	4.02
FeO	1.43	2.0	9.3	2.45
MnO	0.04	0.1	0.2	
MgO	0.29	1.3	4.1	2.44
CaO	1.34	3.2	7.9	3.11
Na_2O	3.74	3.5	3.0	1.30
K_2O	4.27	4.3	1.5	3.24
H_2O	0.17	0.88	1.2	5.00
P_2O_5	0.02	0.22	0.4	0.17
Misc.	———	0.13[e]	———	4.07[f]
TOTAL	99.68	99.96	99.9	99.95
Norm (wt. %)(calculated from chemical composition)				
Quartz	31.20	20.1	3.9	
K-feldspar	25.38	25.7	8.9	
Albite	31.44	30.8	25.2	
Anorthite	6.95	13.4	20.0	

Table 1. Continued

	Granite[a]	Tuff[b]		Basalt[c]	Shale[d]	
Diopside				13.9		
Wollastonite		0.6				
Enstatite		3.2				
Ferrosilite		0.8				
Hypersthene	2.55			15.3		
Enstatite						
Ferrosilite						
Ilmenite	0.30	1.0		3.8		
Magnetite	0.93	3.9		3.7		
Apatite		0.5		0.9		
TOTAL	98.75	100.00		98.6		
Mode (measured) (volume %)						
Quartz	33.0	2.2	phenocrysts		Quartz	30.8
K-feldspar	32	1.3			Feldspar	4.5
Plagioclase	34	35				
Biotite	2	5.4			Fe-oxides	<0.5
Amphibole (hornblende)	1	<1			Carbonates	3.6
Magnetite		1.8			Organic matter	1
Orthopyroxene	0.5			<5		
Clinopyroxene		1.5		<5	Clays	59.9[g]
Olivine				<5		

Table 1. Continued

	Granite[a]	Tuff[b]	Basalt[c]	Shale[d]
Matrix		52[h]	>90[i]	
An content of Plagioclase (mole %)	21	36	63	
TOTAL	102.5	100.2	100.0	100.39

[a] Rubidoux Granite, California, sample E1-167, Larsen, 1948, GSA Mem. 29.

[b] Snowshoe Mtn. Quartz Latite, Colorado, sample S-56A, Ratte and Steven, 1967, USGS Prof. Paper 524-H.

[c] Average Yakima basalt (analysis b, p. 593), Columbia River Plateau, Washington-Oregon, Waters, 1961, AJS, 259, 583-611.

[d] Average shale, Shaw and Weaver, 1965, J. Sed. Pet., 35, 213-222.

[e] CO_2

[f] CO_2+SO_3+C

[g] Clays include: illite and mixed-layer clays, kaolinite, and chlorite (listed in order of decreasing abundance).

[h] Matrix comprises: 1) glass + alteration products in welded tuff, 2) microcrystalline intergrowth of plagioclase and cristobalite in devitrified tuffs, and 3) clays + zeolite minerals in altered tuffs.

[i] Matrix comprises: intergrown microcrystalline clinopyroxene (pigeonite), orthopyproxene, and plagioclase with minor cristobalite (listed in order of decreasing abundance).

3. Summary of available experimental data on the thermodynamic properties of minerals

Table 2 summarizes the experimental data on heat capacity (Cp), relative enthalpy (H_T-H_{298}), entropy (S), enthalpy of formation (H), enthalpy of reaction (H), Gibbs energy of reaction (G), molar volume (V), volume thermal expansion (dV/dT), and volume compressibility (dV/dP) available for the mineral phases of interest. The symbols in the above parentheses identify the type of data in Table 2. An X in the column under a data-type symbol indicates experimental information is available on that thermodynamic property for the phase. If heat capacity or relative enthalpy data are available, the temperature range (above 298 K) of the measured data is given.

Indirect constraints on thermodynamic properties caused by the functional relationships among thermodynamic properties are not shown in the table. Measurement of Gibbs energy at different temperatures for a phase constrains the properties of enthalpy and entropy for the phase if the heat capacity is known. For example, no experimental calorimetic data on entropy or enthalpy exist for anthophyllite; however, data on a series of phase equilibrium studies (Gibbs energy of reaction) and heat capacity are available and cover a sufficiently broad temperature range to constrain the properties of entropy and enthalpy.

Where data are lacking or insufficient, estimates of the thermodynamic properties are needed to evaluate the properties of the phase. In most cases only heat capacity, volume thermal expansion, and volume compressibility need to be estimated, and these properties may be estimated with an accuracy of a few percent. For example, the heat capacity of hedenbergite will need to be estimated to evaluate the available phase equilibria data and derive entropy, enthalpy, and Gibbs energy properties. Phases lacking data on heat capacity, entropy, and enthalpy and having only one measured value of Gibbs energy (epistilbite, heulandite, Na-montmorillonite, and stilbite in this compilation) need estimated values for heat capacity and entropy. Molar entropy also may be estimated using the techniques developed by Helgeson and others (1978, AJS, 278-A, 229 p.) and Cantor (1977, Science, 198, 206-207).

The information summarized on Table 2 indicate that it should be possible to derive internally consistent thermodynamic properties for most of the tabulated phases. The symbols in the left-hand column of Table 2 identify the repository rock type commonly containing the mineral as a component.

Table 3 contains all the available experimental data listed by reference citation for each mineral phase in Table 2. These citations have been through a preliminary evaluation in that 1) we reviewed each citation to insure there were no obvious errors in experimental technique and 2) we determined that there was no obvious ambiguity in the identification of the phases.

We are aware of conflicts in the cited experimental data, but these cannot be resolved at this time. To resolve them, one must compare the conflicting data with theory and with other properties measured on the phase (or phases) in the data sets. This can be done best during the correlation procedure!

Table 2. Summary of available experimental data on thermodynamic properties of minerals

Rock type[a]	Mineral/phase	Formula	Cp (H_T-H_{298})	Cp (H_T-H_{298}) - range (T/K)	S	H	G	V	dV/dT	dV/dP
G,S,Ta,Ba	Albite - low	$NaAlSi_3O_8$	X	298 - 1373	X	X	X	X	X	X
G,Sa	Almandine	$Fe_3Al_2Si_3O_{12}$						X	X	X
G,T	Analbite	$NaAlSi_3O_8$	X	298 - 1000	X	X	X	X	X	
Ta,Ba	Analcite	$NaAlSi_2O_6 \cdot H_2O$	X	298 - 998	X	X	X	X		X
Sa	Andalusite	Al_2SiO_5	X	298 - 1600	X	X	X	X	X	X
Ba	Andradite	$Ca_3Fe_2Si_3O_{12}$	X	298 - 1100			X	X		
G,T,Sa	Annite	$KFe_3AlSi_3O_{10}(OH)_2$	X	335 - 700			X	X		
B	Anorthite	$CaAl_2Si_2O_8$	X	298 - 1673	X	X	X	X	X	
Ba	Anthophyllite	$Mg_7Si_8O_{22}(OH)_2$	X	350 - 1000			X	X		
Ba	Antigorite	$Mg_{48}Si_{34}O_{85}(OH)_{62}$	X	298 - 848	X		X	X		
Ba	Aragonite	$CaCO_3$	X	298 - 600	X	X	X	X	X	
Sa	Boehmite	$AlO(OH)$	X	298	X		X	X		
Ba	Brucite	$Mg(OH)_2$	X	298 - 699	X	X	X	X	X	
Ta,Ba,S	Calcite	$CaCO_3$	X	298 - 1200	X	X	X	X	X	X
B	Ca-Al Clinopyroxene	$CaAl_2SiO_6$	X	298 - 1000		X	X	X		
	Carbon dioxide	CO_2	X	298 - 6000	X	X	X	X	X	X
Ba	Chrysotile	$Mg_2Si_2O_5(OH)_4$	X	298	X	X	X	X		

Table 2. Continued

Rock type[a]	Mineral/phase	Formula	Cp (H_T-H_{298})	Cp (H_T-H_{298}) - range (T/K)	S	H	G	V	dV/dT	dV/dP
S,Ba	Clinochlore	$Mg_5Al_2Si_3O_{10}(OH)_4$					X	X		
B,T	Clinoenstatite	$MgSiO_3$	X	298 - 1800	X	X	X	X	X	
B,T	Clinoferrosilite	$FeSiO_3$					X	X		
	Corundum	Al_2O_3	X	298 - 6000	X	X	X	X	X	X
Ta	Cristobalite	SiO_2	X	298 - 3000	X	X	X	X	X	
Sa	Diaspore	$AlO(OH)$	X	298 - 509	X		X	X		
S	Dickite	$Al_2Si_2O_5(OH)_4$	X	298	X	X		X		
B,T	Diopside	$CaMg(SiO_3)_2$	X	298 - 1600	X	X	X	X	X	X
S,Ba,Ta	Dolomite	$CaMg(CO_3)_2$	X	298 - 800	X	X	X	X		
B,T	Enstatite	$MgSiO_3$				X	X	X	X	X
Ga,Ta,Ba,S	Epidote	$Ca_2FeAl_2Si_3O_{12}(OH)$	X	335 - 1100			X	X		
Ta,Ba	Epistilbite	$CaAl_2Si_6O_{16} \cdot 5H_2O$					X	X		
T,Ba	Fayalite	Fe_2SiO_4	X	298 - 1727	X	X	X	X	X	X
T,B	Ferrosilite	$FeSiO_3$					X	X		
B	Forsterite	Mg_2SiO_4	X	298 - 1808	X	X	X	X	X	X
Sa	Gibbsite	$Al(OH)_3$	X	298 - 400	X	X		X		
S	Graphite	C	X	298 - 6000	X	X	X	X	X	

Table 2. Continued

Rock type[a]	Mineral/phase	Formula	Cp (H_T-H_{298})	Cp (H_T-H_{298}) - range (T/K)	S	H	G	V	dV/dT	dV/dP
Ba,Sa	Grossular	$Ca_3Al_2Si_3O_{12}$	X	298 - 987	X	X	X	X	X	X
S	Halloysite	$Al_2Si_2O_5(OH)_4$	X	298	X	X				
B	Hedenbergite	$CaFe(SiO_3)_2$					X	X	X	X
Ba,Ta,Ga,S	Hematite	Fe_2O_3	X	298 - 1757	X		X	X	X	
Ta,Ba	Heulandite	$CaAl_2Si_7O_{18}\cdot 6H_2O$					X	X		
S	Illite	$(K,H_3O)_{x+y}(Mg,Fe)_xAl_{2-x+y}Si_{4-y}O_{10}(OH)_2\cdot$ $(1-x-y-z)H_2O \quad x+y+z \leq 1$	X	298 - 380	X					
S,Ta	Kaolinite	$Al_2Si_2O_5(OH)_4$	X	298 - 800	X	X	X	X		
Sa	Kyanite	Al_2SiO_5	X	298 - 1503	X	X	X	X	X	X
T,Ba	Laumontite	$CaAl_2Si_4O_{12}\cdot 4H_2O$					X	X		
Ta,Ba	Lawsonite	$CaAl_2Si_2O_7(OH)_2\cdot H_2O$	X	298	X	X	X	X		
Ta,Ba	Leonhardite	$Ca_2Al_4Si_8O_{24}\cdot 7H_2O$	X	298	X			X		
Ba	Magnesite	$MgCO_3$	X	298 - 743	X		X	X		
Ta,Ba,Ga,S	Magnesiocalcite	$(Ca,Mg)CO_3$					X	X		
G,S,T,B	Magnetite	Fe_3O_4	X	298 - 1825	X		X	X	X	
S	Margarite	$CaAl_4Si_2O_{10}(OH)_2$	X	298 - 1000	X		X	X		
S,G,T	Microcline	$KAlSi_3O_8$	X	298 - 1400	X	X		X		X

Table 2. Continued

Rock type[a]	Mineral/phase	Formula	Cp (H_T-H_{298})	Cp (H_T-H_{298}) - range (T/K)	S	H	G	V	dV/dT	dV/dP
G,S,Ta	Muscovite	$KAl_3Si_3O_{10}(OH)_2$	X	298 - 967	X	X	X	X		
S,Ta	Na-Beidellite	$Na_{.33}Al_2(Al_{.33}Si_{3.67})O_{10}(OH)_2$					X			
S	Paragonite	$NaAl_3Si_3O_{10}(OH)_2$	X	298 - 800	X		X	X		
B	Phlogophite	$KMg_3AlSi_3O_{10}(OH)_2$	X	335 - 1100			X	X	X	X
Ba,Ta	Prehnite	$Ca_2Al_2Si_3O_{10}(OH)_2$	X	298 - 800	X		X	X		
B,Ta,S,G	Pyrite	FeS_2	X	298 - 1000	X		X	X		
Ba	Pyrope	$Mg_3Al_2Si_3O_{12}$	X	298 - 1000	X	X	X	X	X	X
S,Ta	Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	X	298 - 680	X		X	X	X	
S,Ba	Pyrrhotite	$Fe_{1-x}S$	X	298 - 2000	X	X	X	X	X	
G,S,T	Quartz	SiO_2	X	298 - 2000	X	X	X	X	X	X
T,G	Sanidine	$KAlSi_3O_8$	X	298 - 1400	X	X	X	X		
	Steam	H_2O (gas)	X	398 - 6000	X	X	X	X	X	X
Ta,Ba	Stilbite	$CaAl_2Si_7O_{18}\cdot 7H_2O$					X	X		
Ba	Talc	$Mg_3Si_4O_{10}(OH)_2$	X	298 - 800	X	X	X	X	X	X
Ba	Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$	X	298 - 800	X	X	X	X	X	X
Ta,Ba	Wairakite	$CaAl_2Si_4O_{12}\cdot 2H_2O$					X	X		

Table 2. Continued

Rock type[a]	Mineral/phase	Formula	Cp (H_T-H_{298})	Cp (H_T-H_{298}) - range (T/K)	S	H	G	V	dV/dT	dV/dP
	Water	H_2O (liquid)	X	298 - 398	X	X	X	X	X	X
B	Wollastonite	$CaSiO_3$	X	298 - 1673	X	X	X	X	X	X
G,Ta,Ba,S	Zoisite	$Ca_2Al_3Si_3O_{12}(OH)$	X	298 - 730	X		X	X		

[a] Rock type typically containing the mineral phase as a component. Notation:

granite (G); altered granite (Ga)
tuff (T); altered tuff (Ta)
basalt (B); altered basalt (Ba)
shale (S); altered shale (Sa)

Table 3.

All experimental data surveyed on the thermodynamic properties of selected minerals/phases

All available experimental data surveyed on the thermodynamic properties of selected minerals/phases

This table of experimental data is arranged alphabetically by mineral name. The table includes mineral name, formula, mineral group, solid solution variability, and a summary of experimental data on the thermodynamic properties of minerals. The summary of experimental data includes literature citation, data type, temperature/pressure range of measurement, and the phases involved in the study. The legend for the phase codes (shown under the "Phases studied" heading) is given in Table 4.

The notation for data type is as follows:

Cp - heat capacity. Heat capacity typically is measured using low-temperature calorimetry or differential scanning calorimetry.

H_T-H_R - relative enthalpy. Relative enthalpy typically is measured by drop calorimetry.

S - entropy. Third-law entropy is calculated by integration of heat capacity from low-temperature calorimetry. Configurational or magnetic contributions to entropy may need to be added to the third-law entropy value.

H - enthalpy. Data on enthalpy of formation and enthalpy of reaction are included in this category. These properties typically are measured using solution calorimetry or combustion calorimetry. The reaction studied is given under the "Phases studied" heading for each citation.

G - Gibbs energy. Data on Gibbs energy of reaction are included in this category and are measured by phase equilibria studies, electromotive force measurements (emf), or determination of equilibrium constants. The reaction studied is given under the "Phases studied" heading for each citation.

V - molar volume and changes in response to changes in temperature or pressure. The volume properties are typically measured by x-ray diffraction techniques or physical measurements of size or density.

dH/dX - partial molar enthalpy. Partial molar enthalpy is determined by solution calorimetry measurements on a mineral series with variable composition. The composition range of the study is shown in the parenthesis given under the "Phases studied" heading for each citation.

a - chemical potential (activity). Chemical potential is determined by phase equilibria studies among phases of variable, but known, composition. The composition range of the study is shown in the parenthesis given under the "Phases studied" heading for each citation.

dV/dX - partial molar volume. Partial molar volume typically is measured by x-ray diffraction techniques on a mineral series with variable composition. The composition range of the study is shown in the parenthesis given under the "Phases studied" heading for each citation.

Albite - low $NaAlSi_3O_8$ - Feldspar group Alb

Al,Si ordered in tetrahedral sites

Important solid solution

(Na,K) Albite, low - Microcline join (alkali Feldspar series)

(NaSi,CaAl) Albite, low - Anorthite join (Plagioclase series)

(AlSi order, AlSi disorder in tetrahedral sites) Albite, low - Analbite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemingway & others, manuscript	Cp	350-1000 K/1 atm	Alb
Kelley & others, 1953, US Bur. Mines Rpt. Inv. 4955, 21 p	Cp	54-297 K/1 atm	Alb
Openshaw & others, 1976, USGS J. Res., 4, 195-204	Cp	16-373 K/1 atm	Alb
Kelley & others, 1953, US Bur. Mines Rpt. Inv. 4955, 21 p	H_T-H_R	473-1270 K/1 atm	Alb
White, 1919, AJS, 47, 1-59	H_T-H_R	100-1100°C/1 atm	Alb=Ana
Kelley & others, 1953, US Bur. Mines Rpt. Inv. 4955, 21 p	S	298.15 K/1 atm	Alb
Openshaw & others, 1976, USGS J. Res., 4, 195-204	S	298.15 K/1 atm	Alb
Hemingway & Robie, 1977, USGS J. Res., 5, 413-429	H	25°C/1 atm	Alb
Kracek & others, 1951, Wash. Acad. Sci. J., 41, 373-383	H	74.7°C/1 atm	Alb
Newton & others, 1980, Geochim. Cosmo. Acta, 44, 933-941	H	970 K/1 atm	Alb=Ana
Campbell & Fyfe, 1965, AJS, 263, 807-816	G	175-210°C/8.9-19 bars	$Anl+Qza=Alb+H_2O$
Edgar, 1978, Neues Jahrb. Min., M., 5, 210-222	G	525-555°C/1000 bars	$Anl=Alb+Nep+H_2O$
Greenwood, 1961, JGR, 66, 3923-3946	G	400-577°C/125-2010 bars	$Anl=Alb+Nep+H_2O$
Gusynin, 1974, Ocherki Fiz.-Khim. Pet., 4, 23-28	G	510-650°C/1000-4000 bars	$Anl=Alb+Nep+H_2O$
Hemley & others, 1961, USGS Prof. Paper 424-D, 338-340	G	330°C/1000 bars	Nmt+Alb=Qza+Par
Liou, 1971, Lithos, 4, 389-402	G	178-210°C/2000-5000 bars	$Ana+Qza=Alb+H_2O$
Liou, 1971, Lithos, 4, 389-402	G	486-604°C/500-3000 bars	$Anl=Alb+Nep+H_2O$

Manghani, 1970, Phys. Earth Planet. Int., 3, 456-461	G	550-625°C/2500-4500 bars	Anl=Alb+Nep+H_2O
Thompson, 1971, AJS, 271, 79-92	G	150-200°C/2000-5500 bars	Anl+Qza=Alb+H_2O
Hovis & Perkins, 1978, Cont. Min. Pet., 66, 345-349	V	25°C/1 atm	Alb
Kozu & Veda, 1933, Proc. Imp. Acad. Japan, 9, 262-264	V	20-1000°C/1 atm	Alb
Openshaw & others, 1976, USGS J. Res., 4, 195-204	V	25°C/1 atm	Alb
Stewart & von Limbach, 1967, Am. Min., 52, 389-413	V	26-1127°C/1 atm	Alb
Yoder & Weir, 1951, AJS, 249, 683-694	V	24-800°C/1 atm	Alb
Yoder & Weir, 1951, AJS, 249, 683-694	V	24°C/2000-10000 atm	Alb
Orville, 1967, Am. Min., 52, 55-86	dV/dX	25°C/1 atm	Mic+Alb($KAlSi_3O_8$-$NaAlSi_3O_8$ join)

Almandine $Fe_3Al_2Si_3O_{12}$ - Garnet group

Important solid solution

(Fe,Mg) Almandine - Pyrope join

(Fe,Mn) Almandine - $Mn_3Al_2Si_3O_{12}$ join

Minor solid solution

(Fe,Ca) Almandine - Grossular join

($Fe_3^{+2}Al_2$,$Ca_3Fe_2^{+3}$) Almandine - Andradite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Holdaway & Lee, 1977, Cont. Min. Pet., 63, 175-198	G	624-775°C/2700-3800 bars	Fec=Alm+Sil+Qza+H_2O
Liou, 1973, J. Pet., 14, 381-413	G	630-762°C/2000-5000 bars	Ept+Mgt=(Gro+Adr+Alm)+Ano+Qza+Hem+H_2O
Richardson, 1968, J. Pet., 9, 467-488	G		Fec=Alm+Sil+Qza+H_2O
Adams & Gibson, 1929, Proc. Nat. Acad. Sci., 15, 713-724	V	25°C/2000-12000 bars	Alm
Lieberman & Gandall, 1952, J. Am. Ceram. Soc., 35, 304-308	V	293-343 K/1 atm	Alm
Sato & others, 1978, JGR, 83, 335-338	V	25°C/18600-98100 bars	Alm
Skinner, 1956, Am. Min., 41, 428-436	V	25°C/1 atm	Alm
Cressy & others, 1978, Cont. Min. Pet., 67, 397-404	a	850-1100°C/10000-22700 bars	Gro+Alm($Ca_3Al_2Si_3O_{12}$-$Fe_3Al_2Si_3O_{12}$ join)
Cressy & others, 1978, Cont. Min. Pet., 67, 397-404	dV/dX	25°C/1 atm	Gro+Alm($Ca_3Al_2Si_3O_{12}$-$Fe_3Al_2Si_3O_{12}$ join)

Analbite $NaAlSi_3O_8$ - Feldspar group

Al,Si disordered in tetrahedral sites

Important solid solution

(Na,K) Analbite - Sanidine join (alkali Feldspar series)

(NaSi,CaAl) Analbite - Anorthite join (Plagioclase series)

(AlSi disorder, AlSi order in tetrahedral sites) Analbite - Albite, low join (Na-Feldspar series)

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemingway & others, unpubl.	Cp	350-1000 K/1 atm	Ana
Openshaw & others, 1976, USGS J. Res., 4, 195-204	Cp	16-375 K/1 atm	Ana
White, 1919, AJS, 47, 1-59	H_T-H_R	100-1100°C/1 atm	Alb=Ana
Openshaw & others, 1976, USGS J. Res., 4, 195-204	S	298.15 K/1 atm	Ana
Hemingway & others, unpubl.	H	25°C/1 atm	Ana
Holm & Kleppa, 1968, Am. Min., 53, 123-133	H	700°C/1 atm	Ana
Hovis & Waldbaum, 1977, Am. Min., 62, 680-686	H	49.7°C/1 atm	Ana
Hovis & Waldbaum, 1977, Am. Min., 52, 680-686	H	49.7°C/1 atm	San+Ana($KAlSi_3O_8$-$NaAlSi_3O_8$ join)
Newton & others, 1980, Geochim. Cosmo. Acta, 44, 933-941	H	970 K/1 atm	Alb=Ana
Thompson & others, 1972, The Feldspars, NATO Adv. Study Inst., 218-248	H	25°C/1 atm	Ana
Birch & LeComte, 1960, AJS, 258, 209-217	G	802-1007°C/21280-26040 bars	Ana=Jad+Qza
Chatterjee, 1970, Cont. Min. Pet., 27, 244-257	G	530-670°C/1000-7000 bars	Par=Ana+Cor+H_2O
Chatterjee, 1972, Cont. Min. Pet., 34, 288-303	G	470-600°C/1000-5000 bars	Par+Qza=Ana+And+H_2O
Chatterjee, 1972, Cont. Min. Pet., 34, 288-303	G	570-640°C/5000-7000 bars	Par+Qza=Ana+Kya+H_2O
Essene & others, 1972, EOS, 53, 544	G	800-1200°C/18500-29000 bars	Jad+Kya=Ana+Cor
Essene & others, 1972, EOS, 53, 544	G	800-1200°C/20500-31000 bars	Ana=Jad+Qza
Gusynin & Ivanov, 1971, Dokl. Akad. Nauk SSSR, 197, 1169-1170	G	490-510°C/1000 bars	Par+Qza=Ana+And+H_2O
Gusynin & Ivanov, 1971, Dokl. Akad. Nauk SSSR, 197, 1169-1170	G	530-550°C/1000 bars	Par=Ana+Cor+H_2O

Holland, 1980, Am. Min., 65, 129-134	G	600-1200°C/16000-33000 bars	Ana=Jad+Qza
Johannes & others, 1971, Cont. Min. Pet., 32, 24-38	G	600°C/15700-16800 bars	Ana=Jad+Qza
Liou, 1971, Lithos, 4, 389-402	G	178-210°C/2000-5000 bars	Ana+Qza=Alb+H_2O
Newton & Kennedy, 1968, AJS, 266, 728-735	G	500-600°C/8000-12300 bars	Ana+Nep=Jad
Newton & Smith, 1967, J. Geol., 75, 268-286	G	500-600°C/13500-16900 bars	Ana=Jad+Qza
Hovis, 1977, Am. Min., 62, 672-679	V	25°C/1 atm	Ana
Newton & others, 1980, Geochim. Cosmo. Acta, 44, 933-941	V	25°C/1 atm	Ana
Openshaw & others, 1976, USGS J. Res., 4, 195-204	V	25°C/1 atm	Ana
Stewart & von Limbach, 1967, Am. Min., 52, 389-413	V	26-1026°C/1 atm	Ana
Sueno & others, 1973, EOS, 54, 1230	V	24-1080°C/1 atm	Ana
Winter & others, 1979, Am. Min., 64, 409-423	V	25-1080°C/1 atm	Ana
Newton & others, 1980, Geochim. Cosmo. Acta, 44, 933-941	dH/dX	970 K/1 atm	Ana+Ano($NaAlSi_3O_8$-$CaAl_2Si_2O_8$ join)
Orville, 1972, AJS, 272, 234-272	a	700°C/2000 bars	Ana+Ano($NaAlSi_3O_8$-$CaAl_2Si_2O_8$ join)
Waldbaum & Robie, 1971, Z. Krist., 134, 381-420	dH/dX	49.7°C/1 atm	San+Ana($KAlSi_3O_8$-$NaAlSi_3O_8$ join)
Hovis, 1977, Am. Min., 62, 672-679	dV/dX	25°C/1 atm	San+Ana($KAlSi_3O_8$-$NaAlSi_3O_8$ join)
Newton & others, 1980, Geochim. Cosmo. Acta, 44, 933-941	dV/dX	25°C/1 atm	Ana+Ano($NaAlSi_3O_8$-$CaAl_2Si_2O_8$ join)
Orville, 1967, Am. Min., 52, 55-86	dV/dX	25°C/1 atm	San+Ana($KAlSi_3O_8$-$NaAlSi_3O_8$ join)

Analcite $NaAlSi_2O_6 \cdot H_2O$ - Zeolite group

Important solid solution

$(H_2O,[])$ $NaAlSi_2O_6 \cdot H_2O$ - $NaAlSi_2O_6 \cdot []$ join

$(NaAl,[]Si)$ $NaAlSi_2O_6 \cdot H_2O$ - $[]Si_3O_6 \cdot H_2O$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5855, 8 p	Cp	53-297 K/1 atm	Anl
King, 1955, J. Am. Chem. Soc., 77, 2192-2193	Cp	53-296 K/1 atm	Anl
Pankratz, 1968, US Bur. Mines Rpt. Inv. 7073, 8 p	H_T-H_R	408-998 K/1 atm	Anl
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5855, 8 p	S	298.15 K/1 atm	Anl
Barany, 1962, US Bur. Mines Rpt. Inv. 5900, 17 p	H	73.7°C/1 atm	Anl
Campbell & Fyfe, 1965, AJS, 263, 807-816	G	175-210°C/8.9-19 bars	$Anl+Qza=Alb+H_2O$
Edgar, 1978, Neues Jahrb. Min., M., 5, 210-222	G	525-555°C/1000 bars	$Anl=Alb+Nep+H_2O$
Greenwood, 1961, JGR, 66, 3923-3946	G	400-577°C/125-2010 bars	$Anl=Alb+Nep+H_2O$
Gusynin, 1974, Ocherki Fiz.-Khim. Pet., 4, 23-28	G	510-650°C/1000-4000 bars	$Anl=Alb+Nep+H_2O$
Liou, 1971, Lithos, 4, 389-402	G	486-604°C/500-3000 bars	$Anl=Alb+Nep+H_2O$
Manghani, 1970, Phys. Earth Planet. Int., 3, 456-461	G	350-600°C/7000-10000 bars	$Anl=Jad+H_2O$
Manghani, 1970, Phys. Earth Planet. Int., 3, 456-461	G	550-625°C/2500-4500 bars	$Anl=Alb+Nep+H_2O$
Thompson, 1971, AJS, 271, 79-92	G	150-200°C/2000-5500 bars	$Anl+Qza=Alb+H_2O$
Edgar, 1978, Neues Jahrb. Min., M., 5, 210-222	V	25°C/1 atm	Anl
Saha, 1959, Am. Min., 44, 300-313	V	25°C/1 atm	Anl
Vaidya & others, 1973, JGR, 78, 6893-6898	V	25°C/5000-45000 bars	Anl
Yoder & Weir, 1960, AJS, 258-A, 420-433	V	25°C/1000-10000 bars	Anl

Andalusite Al_2SiO_5 - trimorph with Kyanite, Sillimanite

Reference	Data type	Range (Temperature/pressure)	Phases studied
Todd, 1950, J. Am. Chem. Soc., 72, 4742-4743	Cp	206-296 K/1 atm	And
Pankratz & Kelley, 1964, US Bur. Mines Rpt. Inv. 6555, 7 p	H_T-H_R	397-1600 K/1 atm	And
Todd, 1950, J. Am. Chem. Soc., 72, 4742-4743	S	298.15 K/1 atm	And
Anderson & others, 1977, AJS, 277, 585-593	H	973 K/1 atm	Cor+Qza=And
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	520-705°C/500-5000 bars	Mus+Qza=San+And+H_2O
Chatterjee, 1972, Cont. Min. Pet., 34, 288-303	G	470-600°C/1000-5000 bars	Par+Qza=Ana+And+H_2O
Gusynin & Ivanov, 1971, Dokl. Akad. Nauk SSSR, 197, 1169-1170	G	490-510°C/1000 bars	Par+Qza=Ana+And+H_2O
Haas & Holdaway, 1973, AJS, 273, 449-464	G	618-722 K/2400-7000 bars	Pyr+Dia=And+H_2O
Haas & Holdaway, 1973, AJS, 273, 449-464	G	643-737 K/2400-7000 bars	And+Qza+H_2O=Pyr
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	623-663 K/1000 bars	Dia+Qza=And+H_2O
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	723-773 K/1000 bars	Cor+Qza=And
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	613-673 K/1000 bars	And+Qza+H_2O=Pyr
Holdaway, 1971, AJS, 271, 97-131	G	650-858 K/2400-4800 bars	Kya=And
Holdaway, 1971, AJS, 271, 97-131	G	764-917 K/1800-3650 bars	And=Sil
Kerrick, 1968, AJS, 266, 204-214	G	668-718 K/1800-3900 bars	And+Qza+H_2O=Pyr
Kerrick, 1972, AJS, 272, 946-958	G	600-610°C/2000 bars	Mus+Qza=San+And+H_2O
Newton, 1966, Sci., 153, 170-172	G	973-1123 K/6100-7400 bars	Kya=And
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	763-833 K/4000-5000 bars	Ano+And+H_2O=Mar+Qzb
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	788-833 K/4000-5000 bars	Ano+And+H_2O=Mar+Qza
Thompson, 1976, Prog. Exp. Pet., Ser. D(6-1976), 12-13	G	390-465°C/500-2000 bars	Ccl+And+Qza=Ano+CO_2
Brace & others, 1969, JGR, 74, 2089-2098	V	25°C/1000-40000 bars	And
Skinner & others, 1961, AJS, 259, 651-668	V	17-1008°C/1 atm	And
Winter & Ghose, 1979, Am. Min., 64, 573-586	V	25-1000°C/1 atm	And

Andradite $Ca_3Fe_2Si_3O_{12}$ - Garnet group

Important solid solution

(Fe^{+3},Al^{+3})	Andradite - Grossular join

Minor solid solution

$(CaFe^{+3},FeAl^{+3})$	Andradite - Almandine join
$(CaFe^{+3},MgAl^{+3})$	Andradite - Pyrope join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Kisleva & others, 1972, Geochem. Int., 9, 1087	H_T-H_R	298-1100 K/1 atm	Adr
Gustafson, 1974, J. Pet., 15, 455-496	G	401-529°C/2000 bars	Hed+Bun=Adr+Mag+Qzb+Nic
Gustafson, 1974, J. Pet., 15, 455-496	G	748-797°C/500-2000 bars	Adr+Fay=Mag+Wol+Qzb
Gustafson, 1974, J. Pet., 15, 455-496	G	789-839°C/500-2000 bars	Adr+Nil=Mag+Wol+Nil
Liou, 1973, J. Pet., 14, 381-413	G	630-762°C/2000-5000 bars	$Ept+Mgt=(Gro+Adr+Alm)+Ano+Qza+Hem+H_2O$
Liou, 1974, Am. Min., 59, 1016-1025	G	570-610°C/500-2000 bars	Adr+Qza+Fay=Hed+Wol
Liou, 1974, Am. Min., 59, 1016-1025	G	621-683°C/500-2000 bars	Adr+Qza+Nic=Hed+Wol+Bun
Taylor & Liou, 1978, Am. Min., 63, 378-393	G	498-600°C/2000 bars	$Qza+Ccl+Hem=Adr+CO_2$
Gustafson, 1974, J. Pet., 15, 455-496	V	25°C/1 atm	Adr
Huckenholz & Yoder, 1971, Neues Jahrb. Min., A., 114, 246-280	V	25°C/1 atm	Adr

Annite $KFe_3AlSi_3O_{10}(OH)_2$ - Mica group, Biotite series Ann

Important solid solution

$(Fe^{+2}H,Fe^{+3})$	Annite - $KFe^{+2}Fe_2^{+3}AlSi_3O_{10}(O[\,])_2$ join
$(Fe^{+2}Si,Al_2)$	Annite - $KFe_2Al_3Si_2O_{10}(OH)_2$ join
(Fe^{+2},Mg^{+2})	Annite - Phlogophite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Melchakova & Topor, 1973, Moscow Univ. Geol. Bull., 28, 102-107	H_T-H_R	335-700 K/1 atm	Ann
Oay, 1971, PhO Thesis, Brown Univ.	G		Fec+San+H_2O=Ann+Sil+Qza
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	540-550°C/1035 bars	Ann+Qzb+Irn=San+Fay+Wus+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	610-640°C/1035-2070 bars	Ann+Bun=San+Mag+Nic+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	650-710°C/1035-2070 bars	Ann+Qzb=Mag+San+Fay+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	760-765°C/1035 bars	Ann=Leu+Kal+Fay+Irn+Wus+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	775-790°C/1035 bars	Ann+Mag=San+Wus+H_2O
Holdaway & Lee, 1977, Cont. Min. Pet., 63, 175-198	G	641-710°C/1900-2800 bars	Fec+San+H_2O=Ann+Sil+Qza
Eugster & Wones, 1962, J. Pet., 3, 82-125	V	25°C/1 atm	Ann

Anorthite $CaAl_2Si_2O_8$ - Feldspar group

Important solid solution

(CaAl,NaSi) Anorthite-Albite, low/Analbite join (Plagioclase series)

Reference	Data type	Range (Temperature/pressure)	Phases studied
Krupka & others, 1979, Am. Min., 64, 86-101	Cp	349-966 K/1 atm	Ano
Robie & others, 1978, Am. Min., 63, 109-123	Cp	202-381 K/1 atm	Ano
White, 1919, AJS, 2d ser., 47(277), 1-59	H_T-H_R	1173-1673 K/1 atm	Ano
Robie & others, 1978, Am. Min., 63, 109-123	S	298.15 K/1 atm	Ano
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Ano=Lme+Cor+Qza
Kracek & Neuvonen, 1952, AJS, Bowen Vol., 293-318	H	347.85 K/1 atm	Ano+H_2O=Lme+Gib+Qza
Boettcher, 1970, J. Pet., 11, 337-379	G	1033-1053 K/1000 bars	Ano+Geh=Gro+Cor
Boettcher, 1970, J. Pet., 11, 337-379	G	853-933 K/4000-5300 bars	Gro+Ano+H_2O=Zoi+Qza
Boettcher, 1970, J. Pet., 11, 337-379	G	893-1053 K/3000-5900 bars	Ano+Wol=Gro+Qzb
Boettcher, 1970, J. Pet., 11, 337-379	G	898-928 K/3000 bars	Gro+Ano+Cor+H_2O=Zoi
Chatterjee, 1971, Naturw., 58, 147	G	763-893 K/1000-7000 bars	Ano+Cor+H_2O=Mar
Chatterjee, 1974, Schweiz. Min. Petrogr. Mitt., 54, 753-767	G	763-893 K/1000-7000 bars	Ano+Cor+H_2O=Mar
Crawford & Fyfe, 1965, AJS, 263, 262-270	G	350-515°C/5170-8900 bars	Law=Ano+H_2O
Goldsmith & Newton, 1977, Am. Min., 62, 1063-1081	G	850-900°C/1000 bars	Ano+Cc1=Mei
Goldsmith & Newton, 1977, Am. Min., 62, 1063-1081	G	850-900°C/5000-15000 bars	Ano+Cc2=Mei
Goldsmith, 1980, Am. Min., 65, 272-284	G	1100-1400°C/22000-31000 bars	Ano=Gro+Kya+Qza
Gordon & Greenwood, 1971, Am. Min., 56, 1674-1688	G	700-849°C/2000 bars	Cc1+Ano+Wol=Gro+CO_2
Hays, 1965, Carn. Inst. Wash. Yb., 234-239	G	1473-1523 K/11000-14600 bars	Gro=Ano+Wol+Geh
Hays, 1965, Carn. Inst. Wash. Yb., 234-239	G	1473-1673 K/11000-14600 bars	Ano+Geh+Cor=Cts
Hewitt, O., 1973, Am. Min., 58, 785-791	G	448-610°C/2000-7000 bars	Mus+Cc1+Qza=San+Ano+CO_2+H_2O
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	715-825°C/1000-4000 bars	Ano+Cc1=Gro+Cor+CO_2

Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	725-825°C/1000 bars	Ano+Ccl=Geh+Gro+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	725-825°C/1000-4000 bars	Ano+Wol+Ccl=Gro+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	775-825°C/1000 bars	Ano+Cor+Ccl=Geh+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	850-890°C/1000 bars	Ano+Ccl=Geh+Wol+CO_2
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	1028-1263 K/1000-6000 bars	Ano+Geh=Gro+Cor
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	1125-1423 K/200-10000 bars	Gro=Ano+Wol+Geh
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	848-858 K/1000-3000 bars	Ano+Wol=Gro+Qza
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	888-958 K/4000 bars	Ano+Wol=Gro+Qzb
Juan & Lo, 1971, Proc. Geol. Soc. China, 14, 34-44	G	292-469°C/690-1380 bars	Wai=Ano+Qza+H_2O
Kay & Taylor, 1960, Faraday Soc. Trans., 56, 1372-1386	G	1543 K/1 atm	Ano+Cwo=Geh+Crb
Kay & Taylor, 1960, Faraday Soc. Trans., 56, 1372-1386	G	1653 K/1 atm	Ano=Geh+Cor+Crb
Liou, 1970, Cont. Min. Pet., 27, 259-282	G	325-393°C/500-5000 bars	Wai=Ano+Qza+H_2O
Liou, 1971, Am. Min., 56, 507-531	G	708-828 K/1974-5527 bars	Ano+Wol+H_2O=Pre
Liou, 1973, J. Pet., 14, 381-413	G	630-762°C/2000-5000 bars	Ept+Mgt=(Gro+Adr+Alm)+Ano+Qza+Hem+H_2O
Newton, 1965, J. Geol., 73, 431-441	G	843-1113 K/2000-6800 bars	Gro+Ano+Cor+H_2O=Zoi
Newton, 1966, AJS, 264, 204-222	G	803-923 K/1100-2000 bars	Ano+Wol=Gro+Qza
Newton, 1966, AJS, 264, 204-222	G	973-1023 K/4700-5700 bars	Ano+Wol=Gro+Qzb
Shmulovich, 1974, Geochem. Int., 11, 883-887	G	1133-1153 K/500-700 atm	Gro=Ano+Wol+Geh
Shmulovich, 1977, Geochem. Int., 14, 126-134	G	627-727°C/1000-3920 bars	Ccl+Wol+Ano=Gro+CO_2
Storre & Nitsch, 1972, Cont. Min. Pet., 35, 1-10	G	510-700°C/2000-7000 bars	Zoi+CO_2=Ano+Ccl+H_2O
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	763-833 K/4000-5000 bars	Ano+And+H_2O=Mar+Qzb
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	788-833 K/4000-5000 bars	Ano+And+H_2O=Mar+Qza
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	803-933 K/4000-5000 bars	Ano+Kya+H_2O=Mar+Qza
Strens, 1968, Min. Mag., 36, 864-867	G	770-823 K/2000 bars	Gro+Ano+H_2O=Zoi+Qza
Thompson, 1970, AJS, 269, 267-275	G	300-357°C/1000-6000 bars	Lau=Ano+Qza+H_2O
Thompson, 1976, Prog. Exp. Pet., Ser. D(6-1976), 12-13	G	390-465°C/500-2000 bars	Ccl+And+Qza=Ano+CO_2
Kozu & Veda, 1933, Proc. Imp. Acad. Japan, 9, 262-264	V	20-1000°C/1 atm	Ano

Rigby & others, 1942, Trans. Brit. Ceram. Soc., 41, 123-143	V	100-1200°C/1 atm	Ano
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Ano
Newton & others, 1980, Geochim. Cosmo. Acta, 44, 933-941	dH/dX	970 K/1 atm	Ana+Ano($NaAlSi_3O_8$-$CaAl_2Si_2O_8$ join)
Orville, 1972, AJS, 272, 234-272	a	700°C/2000 bars	Ana+Ano($NaAlSi_3O_8$-$CaAl_2Si_2O_8$ join)
Newton & others, 1980, Geochim. Cosmo. Acta, 44, 933-941	dV/dX	25°C/1 atm	Ana+Ano($NaAlSi_3O_8$-$CaAl_2Si_2O_8$ join)

Anthophyllite $Mg_7Si_8O_{22}(OH)_2$ - Amphibole group

Reference	Data type	Range (Temperature/pressure)	Phases studied
Krupka, unpubl.	Cp	350-1000 K/1 atm	Ant
Weeks, 1956, J. Geol., 64, 456-472	H	81°C/1 atm	Tre=Ran+Ant+Qza+H_2O
Chernosky & Autio, 1979, Am. Min., 64, 294-303	G	647-742°C/500-3000 bars	Tlc=Ant+Qzb+H_2O
Chernosky & Autio, 1979, Am. Min., 64, 294-303	G	664-775°C/500-2000 bars	Ant=Ens+Qzb+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	663-679°C/1000-4000 bars	For+Tlc=Ant+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	694-711°C/2000 bars	Tlc=Ant+Qzb+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	695-711°C/2000 bars	Ant+For=Ens+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	750-775°C/2000-2600 bars	Ant=Ens+Qzb+H_2O
Hemley & others, 1977, AJS, 277, 353-383	G	640-670°C/1000 bars	Ant+Hsl=Tlc+H_2O
Hemley & others, 1977, AJS, 277, 353-383	G	650-670°C/1000 bars	Ant+H_2O=For+Hsl
Hemley & others, 1977, AJS, 277, 353-383	G	660-715°C/1000 bars	Ens+Hsl=Ant+H_2O
Chernosky & Autio, 1979, Am. Min., 64, 294-303	V	25°C/1 atm	Ant
Greenwood, 1963, J. Pet., 4, 317-351	V	25°C/1 atm	Ant

Antigorite $Mg_{48}Si_{34}O_{85}(OH)_{62}$ - Serpentine group Atg

Reference	Data type	Range (Temperature/pressure)	Phases studied
King & others, 1967, US Bur. Mines Rpt. Inv. 6962, 19 p	Cp	53-296 K/1 atm	Atg
King & others, 1967, US Bur. Mines Rpt. Inv. 6962, 19 p	H_T-H_R	405-848 K/1 atm	Atg
King & others, 1967, US Bur. Mines Rpt. Inv. 6962, 19 p	S	298.15 K/1 atm	Atg
Evans & others, 1976, Schweig. Min. Pet. Mitt., 56, 79-93	G	480-660°C/2000-15000 bars	Atg=For+Tlc+H_2O
Hemley & others, 1977, AJS, 277, 353-383	G	300-450°C/1000 bars	Atg+Hsi=Tlc+H_2O
Hemley & others, 1977, AJS, 277, 353-383	V	25°C/1 atm	Atg
Page & Coleman, 1967, USGS Prof. Paper 575-B, 103-107	V	25°C/1 atm	Atg

Aragonite $CaCO_3$ - dimorph with Calcite

Reference	Data type	Range (Temperature/pressure)	Phases studied
Anderson, 1934, J. Am. Chem. Soc., 56, 340-	Cp		Ara
Staveley & Lingford, 1969, J. Chem. Thermo., 1, 1-11	Cp	197-291 K/1 atm	Ara
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	350-600 K/1 atm	Ara
Staveley & Lingford, 1969, J. Chem. Thermo., 1, 1-11	S	298.15 K/1 atm	Ara
Parker & others, 1971, US NBS Tech. Note 270-6, 106 p	H		Ara
Boettcher & Wyllie, 1968, J. Geol., 76, 314-330	G	400-480°C/8200-9600 bars	Cc1=Ara
Boettcher & Wyllie, 1968, J. Geol., 76, 314-330	G	480-800°C/9000-20100 bars	Cc2=Ara
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	G	400-720°C/9000-22000 bars	Mcc+Dol=Ara+Dol
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	G	400°C/8800-9300 bars	Cc1=Ara
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	G	500-600°C/11200-14400 bars	Cc2=Ara
Johannes & Puhan, 1971, Cont. Min. Pet., 31, 28-38	G	100-480°C/4000-11600 bars	Cc1=Ara
Johannes & Puhan, 1971, Cont. Min. Pet., 31, 28-38	G	450-600°C/11500-15500 bars	Cc2=Ara
Kozu & Kani, 1934, Proc. Imp. Acad. Japan, 10, 222-225	V	25-450°C/1 atm	Ara
Swanson & Fuyat, 1953, US NBS Circ. 539, 2, 65 p	V	25°C/1 atm	Ara

Boehmite AlO(OH) - dimorph with Diaspore

Reference	Data type	Range (Temperature/pressure)	Phases studied
Shomate & Cook, 1946, J. Am. Chem. Soc., 68, 2140-2142	Cp	200-296 K/1 atm	Boe
Shomate & Cook, 1946, J. Am. Chem. Soc., 68, 2140-2142	S	298.15 K/1 atm	Boe
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Boe+Qza+H_2O=Kao
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Boe

Brucite $Mg(OH)_2$

Reference	Data type	Range (Temperature/pressure)	Phases studied
Giaugue & Archibald, 1937, J. Am. Chem. Soc., 59, 561-569	Cp	20-300 K/1 atm	Bru
King & others, 1975, US Bur. Mines Rpt. Inv. 8041, 13 p	H_T-H_R	350-699 K/1 atm	Bru
Parker & others, 1971, US NBS Tech. Note 270-6, 106 p	S	298 K/1 atm	Bru
Parker & others, 1971, US NBS Tech. Note 270-6, 106 p	H	298 K/1 atm	Bru
Taylor & Wells, 1938, J. Res. NBS, 21, 133-149	H		$Bru=Per+H_2O$
Barnes & Ernst, 1963, AJS, 261, 129-150	G	544-664°C/240-2000 bars	$Bru=Per+H_2O$
Fyfe & Goodwin, 1962, AJS, 260, 289-293	G	591-620°C/1034 bars	$Bru=Per+H_2O$
Fyfe, 1958, AJS, 256, 729-732	G	530-570°C/200-740 bars	$Bru=Per+H_2O$
Johannes & Metz, 1968, Neues Jahrb. Min., M., 68, 15-26	G	450-600°C/1000 bars	$Mag+H_2O=Bru+CO_2$
Johannes, 1968, Cont. Min. Pet., 19, 309-315	G	330-440°C/500-7000 bars	$Chr+Bru=For+H_2O$
Kennedy, 1956, AJS, 254, 567-573	G	500-600°C/130-1175 bars	$Bru=Per+H_2O$
Walter & others, 1962, J. Pet., 3, 49-64	G	463-666°C/1000-4000 bars	$Mag+H_2O=Bru+CO_2$
Megaw, 1933, Proc. Roy. Soc. Lond., A142, 198-214	V	293-373 K/1 atm	Bru
Roble & others, 1978, USGS Bull. 1452, 456 p	V	25°C/1 atm	Bru
Swanson & others, 1956, US NBS Circ. 539, 6, 62 p	V	25°C/1 atm	Bru

Calcite - I, II $CaCO_3$ - dimorph with Aragonite Ccl,Cc2

Reference	Data type	Range (Temperature/pressure)	Phases studied
Anderson, 1934, J. Am. Chem. Soc., 56, 340-	Cp		Ccl
Jacobs & Kerrick, 1979, EOS, 60, 406	Cp	298-775 K/1 atm	Ccl
Staveley & Lingford, 1969, J. Chem. Thermo., 1, 1-11	Cp	195-303 K/1 atm	Ccl
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	400-1200 K/1 atm	Ccl
Staveley & Lingford, 1969, J. Chem. Thermo., 1, 1-11	S	298.15 K/1 atm	Ccl
Parker & others, 1971, US NBS Tech. Note 270-6, 106 p	H		Ccl
Boettcher & Wyllie, 1968, J. Geol., 76, 314-330	G	400-480°C/8200-9600 bars	Ccl=Ara
Boettcher & Wyllie, 1968, J. Geol., 76, 314-330	G	480-800°C/9000-20100 bars	Cc2=Ara
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	G	400°C/8800-9300 bars	Ccl=Ara
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	G	500-600°C/11200-14400 bars	Cc2=Ara
Goldsmith & Newton, 1977, Am. Min., 62, 1063-1081	G	850-900°C/1000 bars	Ano+Ccl=Mei
Goldsmith & Newton, 1977, Am. Min., 62, 1063-1081	G	850-900°C/5000-15000 bars	Ano+Cc2=Mei
Gordon & Greenwood, 1971, Am. Min., 56, 1674-1688	G	700-849°C/2000 bars	Ccl+Ano+Wol=Gro+CO_2
Greenwood, 1967, Am. Min., 52, 1669-1680	G	558-595°C/1000-2000 bars	Ccl+Qza=Wol+CO_2
Greenwood, 1967, Am. Min., 52, 1669-1680	G	609-723°C/1000-2000 bars	Ccl+Qzb=Wol+CO_2
Harker & Tuttle, 1955, AJS, 253, 209-224	G	980-1120°C/100-500 bars	Ccl=Lme+CO_2
Harker & Tuttle, 1956, AJS, 254, 239-256	G	600-800°C/300-2400 bars	Ccl+Qzb=Wol+CO_2
Haselton & others, 1978, Geophys. Res. Lett., 5, 753-756	G	1000-1325°C/10000-19000 bars	Cc2+Qzb=Wol+CO_2
Hewitt, D., 1973, Am. Min., 58, 785-791	G	448-610°C/2000-7000 bars	Mus+Ccl+Qza=San+Ano+CO_2+H_2O
Hewitt, D., 1973, Am. Min., 58, 785-791	G	539-540°C/6000 bars	Mus+Ccl+Qza=San+Zoi+CO_2+H_2O
Hewitt, D., 1975, Am. Min., 60, 391-397	G	460-681°C/2000-8000 bars	Phl+Ccl+Qza=Tre+San+CO_2+H_2O
Hoschek, 1973, Cont. Min. Pet., 39, 231-237	G	495-635°C/4000-6000 bars	Phl+Ccl+Qza=Tre+San+CO_2+H_2O
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	715-825°C/1000-4000 bars	Ano+Ccl=Gro+Cor+CO_2

Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	715-825°C/1000-4000 bars	Gro+Cor+Ccl=Geh+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	725-825°C/1000 bars	Ano+Ccl=Geh+Gro+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	725-825°C/1000-4000 bars	Ano+Wol+Ccl=Gro+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	755-788°C/1000 bars	Gro+Ccl=Geh+Wol+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	775-825°C/1000 bars	Ano+Cor+Ccl=Geh+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	850-890°C/1000 bars	Ano+Ccl=Geh+Wol+CO_2
Johannes & Puhan, 1971, Cont. Min. Pet., 31, 28-38	G	100-480°C/4000-11600 bars	Ccl=Ara
Johannes & Puhan, 1971, Cont. Min. Pet., 31, 28-38	G	450-600°C/11500-15500 bars	Cc2=Ara
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	310-390°C/4000-7000 bars	Ccl+Pyr+H_2O=Law+Qza+CO_2
Shmulovich, 1977, Geochem. Int., 14, 126-134	G	627-727°C/1000-3920 bars	Ccl+Wol+Ano=Gro+CO_2
Storre & Nitsch, 1972, Cont. Min. Pet., 35, 1-10	G	510-700°C/2000-7000 bars	Zoi+CO_2=Ano+Ccl+H_2O
Taylor & Liou, 1978, Am. Min., 63, 378-393	G	498-600°C/2000 bars	Qza+Ccl+Hem=Adr+CO_2
Thompson, 1976, Prog. Exp. Pet., Ser. D(6-1976), 12-13	G	390-465°C/500-2000 bars	Ccl+And+Qza=Ano+CO_2
Adams & others, 1919, J. Am. Chem. Soc., 41, 12-42	V	25°C/1960-12000 bars	Ccl
Bridgeman, 1939, AJS, 237, 7-18	V	25°C/20000-40000 bars	Cc2
Bridgeman, 1939, AJS, 237, 7-18	V	25°C/5000-10000 bars	Ccl
Chessin & others, 1965, Acta Cryst., 18, 689-693	V	25°C/1 atm	Ccl
Graf, 1961, Am. Min., 46, 1283-1316	V	25°C/1 atm	Ccl
Rao & others, 1968, J. Phys. Chem. Solids, 29, 245-248	V	301-797 K/1 atm	Ccl
Rosenholtz & Smith, 1949, Am. Min., 34, 846-854	V.	20-700°C/1 atm	Ccl
Vaidya & others, 1973, JGR, 78, 6893-6898	V	25°C/20000-45000 bars	Cc2
Vaidya & others, 1973, JGR, 78, 6893-6898	V	25°C/5000-15000 bars	Ccl

Ca-Al Clinopyroxene $CaAl_2SiO_6$ - Pyroxene group   Cts

Important solid solution

$(Al_2,CaSi)$	Ca-Al Clinopyroxene - Wollastonite join
$(Al_2,MgSi)$	Ca-Al Clinopyroxene - Diopside join
$(Al_2,FeSi)$	Ca-Al Clinopyroxene - Hedenbergite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Thompson & others, 1978, EOS, 59, 395	Cp	298.15-1000 K/1 atm	Cts
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Cts=Lme+Cor+Qza
Hays, 1965, Carn. Inst. Wash. Yb., 234-239	G	1473-1673 K/11000-14600 bars	Ano+Geh+Cor=Cts
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Cts
Newton & others, 1977, Geochim. Cosmo. Acta, 41, 369-377	dH/dX	970 K/1 atm	Dio+Cts($CaMgSi_2O_6$-$CaAl_2SiO_6$ join)
Newton & others, 1977, Geochim. Cosmo. Acta, 41, 369-377	dV/dX	25°C/1 atm	Dio+Cts($CaMgSi_2O_6$-$CaAl_2SiO_6$ join)

Carbon Dioxide CO_2 - Gas CO_2

Reference	Data type	Range (Temperature/pressure)	Phases studied
JANAF, 1965	Cp	0-6000 K/1 atm	CO_2
JANAF, 1965	S	0-6000 K/1 atm	CO_2
JANAF, 1965	H	0-6000 K/1 atm	CO_2
Burnham & Wall, unpubl.	P-V-T	177-977°C/1000-10000 bars	CO_2
Greenwood & Barnes. 1966, GSA Mem., 97, 385-400	P-V-T	12-750°C/25-2000 bars	$CO_2+H_2O(CO_2-H_2O$ join)
Greenwood, 1969, AJS, 267-A, 191-208	P-V-T	450-800°C/1-500 bars	$CO_2+H_2O(CO_2-H_2O$ join)
Kennedy & Holser, 1966, GSA Mem., 97, 371-383	P-V-T	0-1000°C/25-1400 bars	CO_2
Liley, 1956, Rpt. Brit. Admir. DEMR/EN/32/16/1/56	P-V-T		$CO_2+H_2O(CO_2-H_2O$ join)
Powell & others, 1979, Prog. Astronau. Aeronau., 66, 325-348	P-V-T	0-900°C/0-10000 bars	$CO_2+H_2O(CO_2-H_2O$ join)
Ryzhenko & Volkov, 1971, Geochem. Int., 8, 468-481	P-V-T	100-400°C/1000-4000 bars	CO_2
Takenouchi & Kennedy, 1964, AJS, 262, 1055-1074	P-V-T	110-350°C/1-1600 bars	$CO_2+H_2O(CO_2-H_2O$ join)

Chrysotile $Mg_2Si_2O_5(OH)_4$ - Serpentine group

Reference	Data type	Range (Temperature/pressure)	Phases studied
King & others, 1967, US Bur. Mines Rpt. Inv. 6962, 19 p	Cp	53-296 K/1 atm	Chr
King & others, 1967, US Bur. Mines Rpt. Inv. 6962, 19 p	S	298.15 K/1 atm	Chr
King & others, 1967, US Bur. Mines Rpt. Inv. 6962, 19 p	H	25°C/1 atm	Chr
Hemley & others, 1977, AJS, <u>277</u>, 322-351	G	90-450°C/1 atm-2000 bars	Chr+Hsi=Tlc+H_2O
Johannes, 1968, Cont. Min. Pet., <u>19</u>, 309-315	G	330-440°C/500-7000 bars	Chr+Bru=For+H_2O
Johannes, 1969, AJS, <u>267</u>, 1083-1104	G	340-490°C/1000-4000 bars	Chr+CO_2=Tlc+Mag+H_2O
Hemley & others, 1977, AJS, <u>277</u>, 322-315	V	25°C/1 atm	Chr
Page & Coleman, 1967, USGS Prof. Paper 575-B, 103-107	V	25°C/1 atm	Chr

Clinochlore $Mg_5Al_2Si_3O_{10}(OH)_4$ - Chlorite group

Important solid solution

(Mg,Fe) $Mg_5Al_2Si_3O_{10}(OH)_4$ - $Fe_5Al_2Si_3O_{10}(OH)_4$ join

(MgSi,Al_2) $Mg_5Al_2Si_3O_{10}(OH)_4$ - $Mg_4Al_4Si_2O_{10}(OH)_4$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Bird & Fawcett, 1973, J. Pet., 14, 415-428	G	634-664°C/8270-9790 bars	$Cln+Mus=Phl+Kya+Qza+H_2O$
Chernosky, 1974, Am. Min., 59, 496-507	G	576-750°C/500-3000 bars	$Cln=For+Spl+Crd+H_2O$
Chernosky, 1978, Am. Min., 63, 73-82	G	504-581°C/2000-4000 bars	$Cln+Qza=Tlc+Crd+H_2O$
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	825-890°C/11000-18000 bars	$Cln=Ens+For+Spl+H_2O$
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	870-900°C/22000-35000 bars	$Cln=Pyp+For+Spl+H_2O$
Widmark, 1980, Cont. Min. Pet., 72, 175-179	G	547-640°C/1000-3000 bars	$Cln+Dol=Spl+For+Mcc+CO_2+H_2O$.
Bird & Fawcett, 1973, J. Pet., 14, 415-428	V	25°C/1 atm	Cln
Chernosky, 1974, Am. Min., 59, 496-507	V	25°C/1 atm	Cln
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	V	25°C/1 atm	Cln

Clinoenstatite $MgSiO_3$ - Pyroxene group; trimorph with Enstatite, Protoenstatite

Important solid solution

(Mg,Ca)	Clinoenstatite - Diopside join
(Mg_2,CaFe)	Clinoenstatite - Hedenbergite join
(Mg_2Si,$CaAl_2$)	Clinoenstatite - Ca-Al Clinopyroxene join
(Mg,Fe)	Clinoenstatite - Clinoferrosilite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	400-1800 K/1 atm	Cen
Kelley & King, 1961, US Bur. Mines Bull. 592, 149 p	S	298 K/1 atm	Cen
Kelley, 1943, J. Am. Chem. Soc., 65, 339-	S	298.15 K/1 atm	Cen
Torgeson & Sahama, 1948, J. Am. Chem. Soc., 70, 2156-2160	H	25°C/1 atm	Cen
Boyd & England, 1965, Carn. Inst. Wash. Yb., 117-123	G	620-760°C/5000-40000 bars	Ens=Cen
Sarver & Hummel, 1962, J. Am. Chem. Soc., 45, 152-156	G	860-870°C/1 atm	Ens=Cen
Morimoto & others, 1960, Z. Krist., 114, 120-147	V	25°C/1 atm	Cen
Perrotta & Stephenson, 1965, Sci., 148, 1090-1091	V	25°C/1 atm	Cen
Rigby & others, 1942, Trans. Brit. Ceram. Soc., 41, 123-143	V	100-1200°C/1 atm	Cen
Sarver & Hummel, 1962, J. Am. Chem. Soc., 45, 152-156	V	200-700°C/1 atm	Cen
Stephenson & others, 1966, Min. Mag., 35, 838-846	V	26°C/1 atm	Cen

Clinoferrosilite $FeSiO_3$ - Pyroxene group; trimorph with Ferrosilite, Protoferrosilite Cfs

Important solid solution

(Fe,Ca)	Clinoferrosilite - Hedenbergite join
(Fe_2,CaMg)	Clinoferrosilite - Diopside join
(Fe_2Si,$CaAl_2$)	Clinoferrosilite - Ca-Al Clinopyroxene join
(Fe,Mg)	Clinoferrosilite - Clinoenstatite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Lindsley, 1965, Carn. Inst. Wash. Yb., 148-150	G	775-825°C/10000-40000 bars	Cfs=Fes
Burnham, 1965, Carn. Inst. Wash. Yb., 202-204	V	25°C/1 atm	Cfs

Corundum Al_2O_3

Reference	Data type	Range (Temperature/pressure)	Phases studied
Chase & others, 1974, J. Phys. Chem. Ref. Data, 3, 311-480	Cp		Cor
Chase & others, 1975, J. Phys. Chem. Ref. Data, 4, 1-176	Cp		Cor
Stull & Prophet, 1971, US NBS NSRDS-NBS 37	Cp		Cor
CODATA Task Group, 1978, CODATA Bull., 28, 1-16	S		Cor
Anderson & Kleppa, 1969, AJS, 267, 285-290	H	974 K/1 atm	Kya=Cor+Qza
Anderson & others, 1977, AJS, 277, 585-593	H	973 K/1 atm	Cor+Qza=And
CODATA Task Group, 1978, CODATA Bull., 28, 1-16	H		Cor
Charlu & others, 1975, Geochim. Cosmo. Acta, 39, 1487-1497	H	970 K/1 atm	Per+Cor=Spl
Charlu & others, 1975, Geochim. Cosmo. Acta, 39, 1487-1497	H	970 K/1 atm	Pyp=Per+Cor+Qzb
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Ano=Lme+Cor+Qza
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Cts=Lme+Cor+Qza
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Gro=Lme+Cor+Qzb
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Sil=Cor+Qzb
Shearer & Kleppa, 1973, J. Inorg. Nuc. Chem., 35, 1073-1078	H	965-1173 K/1 atm	Per+Cor=Spl
Taylor & Schmalzried, 1964, J. Phys. Chem., 68, 2444-	H	530°C/1 atm	Per+Cor=Spl
Tretjakow & Schmalzried, 1965, Ber. Bunsenges. Physik. Chem., 69, 396-	H	1273 K/1 atm	Per+Cor=Spl
Boettcher, 1970, J. Pet., 11, 337-379	G	1033-1053 K/1000 bars	Ano+Geh=Gro+Cor
Boettcher, 1970, J. Pet., 11, 337-379	G	898-928 K/3000 bars	Gro+Ano+Cor+H_2O=Zoi
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	600-800°C/1000-8000 bars	Mus=San+Cor+H_2O
Chatterjee, 1970, Cont. Min. Pet., 27, 244-257	G	530-670°C/1000-7000 bars	Par=Ana+Cor+H_2O
Chatterjee, 1971, Naturw., 58, 147	G	763-893 K/1000-7000 bars	Ano+Cor+H_2O=Mar
Chatterjee, 1974, Schweiz. Min. Petrogr. Mitt., 54, 753-767	G	763-893 K/1000-7000 bars	Ano+Cor+H_2O=Mar
Essene & others, 1972, EOS, 53, 544	G	800-1200°C/18500-29000 bars	Jad+Kya=Ana+Cor

Gusynin & Ivanov, 1971, Dokl. Akad. Nauk SSSR, 197, 1169-1170	G	530-550°C/1000 bars	Par=Ana+Cor+H_2O
Haas, 1972, Am. Min., 57, 1375-1385	G	662-741 K/1750-7000 bars	Dia=Cor+H_2O
Hays, 1965, Carn. Inst. Wash. Yb., 234-239	G	1473-1673 K/11000-14600 bars	Ano+Geh+Cor=Cts
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	723-773 K/1000 bars	Cor+Qza=And
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	715-825°C/1000-4000 bars	Ano+Ccl=Gro+Cor+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	715-825°C/1000-4000 bars	Gro+Cor+Ccl=Geh+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	775-825°C/1000 bars	Ano+Cor+Ccl=Geh+CO_2
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	1028-1263 K/1000-6000 bars	Ano+Geh=Gro+Cor
Kay & Taylor, 1960, Faraday Soc. Trans., 56, 1372-1386	G	1653 K/1 atm	Ano=Geh+Cor+Crb
Newton, 1965, J. Geol., 73, 431-441	G	843-1113 K/2000-6800 bars	Gro+Ano+Cor+H_2O=Zoi
Amatuni & Shevchenko, 1966, Izmer. Tekh., 10, 17-20	V	273-773 K/1 atm	Cor
Finger & Hazen, 1978, J. Appl. Phys., 49, 5823-5826	V	23°C/1-80000 bars	Cor
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Cor
Shalnikova & Yakovelv, 1956, Kristall., 1, 531	V		Cor
Strelkov & others, 1966, Meas. Tech., 9, 1116-1120	V	273-1173 K/1 atm	Cor
d'Amour & others, 1978, J. Appl. Phys., 49, 4411-4416	V	25°C/1-90000 bars	Cor

Cristobalite - alpha, beta SiO_2 - polymorph with Quartz, Tridymite, Coesite, Stishovite   Cra,Crb

Reference	Data type	Range (Temperature/pressure)	Phases studied
JANAF, 1967	Cp	298-1000 K/1 atm	Cra
JANAF, 1967	Cp	298-3000 K/1 atm	Crb
Westrum, 1963, Phys. Chem. Glass, 4, 188-	Cp	5-300 K/1 atm	Cra
JANAF, 1967	S		Cra
JANAF, 1967	S		Crb
Westrum, 1963, Phys. Chem. Glass, 4, 188-	S	298 K/1 atm	Cra
JANAF, 1967	H		Cra
JANAF, 1967	H		Crb
JANAF, 1967	G		Cra
JANAF, 1967	G		Crb
Kay & Taylor, 1960, Faraday Soc. Trans., 56, 1372-1386	G	1543 K/1 atm	Ano+Cwo=Geh+Crb
Kay & Taylor, 1960, Faraday Soc. Trans., 56, 1372-1386	G	1653 K/1 atm	Ano=Geh+Cor+Crb
Kay & Taylor, 1960, Faraday Soc. Trans., 56, 1372-1386	G	1773 K/1 atm	Lme+Crb=Cwo
Johnson & Andrews, 1956, Trans. Brit. Ceram. Soc., 55, 227-236	V	219-1138°C/1 atm	Crb
Johnson & Andrews, 1956, Trans. Brit. Ceram. Soc., 55, 227-236	V	23-208°C/1 atm	Cra
Robie & others, 1978, USGS Bull. 1452, 456 p	V	25°C/1 atm	Cra

Diaspore AlO(OH) - dimorph with Boehmite Dia

Reference	Data type	Range (Temperature/pressure)	Phases studied
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	Cp	206-296 K/1 atm	Dia
Perkins & others, 1979, Am. Min., 64, 1080-1090	Cp	203-345 K/1 atm	Dia
Perkins & others, 1979, Am. Min., 64, 1080-1090	Cp	340-509 K/1 atm	Dia
Perkins & others, 1979, Am. Min., 64, 1080-1090	S	298.15 K/1 atm	Dia
Haas & Holdaway, 1973, AJS, 273, 449-464	G	618-722 K/2400-7000 bars	Pyr+Dia=And+H_2O
Haas, 1972, Am. Min., 57, 1375-1385	G	662-741 K/1750-7000 bars	Dia=Cor+H_2O
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Dia+Qza+H_2O=Kao
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	523-598 K/1000 bars	Dia+Qza=Pyr
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	623-663 K/1000 bars	Dia+Qza=And+H_2O
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Dia

Dickite $Al_2Si_2O_5(OH)_4$ - Clay group; trimorph with Kaolinite, Halloysite

Reference	Data type	Range (Temperature/pressure)	Phases studied
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	Cp	206-296 K/1 atm	Dic
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	S	298.15 K/1 atm	Dic
Barany & Kelley, 1961, US Bur. Mines Rpt. Inv. 5825, 13 p	H	346.85 K/1 atm	Dic+H_2O=Qza+Hlb
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Dic

Diopside $CaMgSi_2O_6$ - Pyroxene group

Important solid solution

(Mg,Fe)	Diopside - Hedenbergite join
($MgSi,Al_2$)	Diopside - Ca-Al Clinopyroxene join
(Ca,Mg)	Diopside - Clinoenstatite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	400-1600 K/1 atm	Dio
Kelley & King, 1961, US Bur. Mines Bull. 592, 149 p	S	298.15 K/1 atm	Dio
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Dio=Lme+Per+Qzb
Kracek & others, 1953, Carn. Inst. Wash. Yb., 69-74	H	74.7°C/1 atm	Dio=Lme+Per+Qza
Navrotsky & Coons, 1976, Geochim. Cosmo. Acta, 40, 1281-1288	H	970 K/1 atm	Dio=Lme+Per+Qzb
Boyd, 1959, Res. Geochem., 1, 377-396	G	800-880°C/575-2000 bars	Tre=Dio+Ens+Qza+H_2O
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	726-774°C/400 bars	Tre=Dio+Ens+Qza+H_2O
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	740-755°C/2000 bars	Tre+San=Phl+Dio+Qza
Adams & Williamson, 1923, J. Franklin Inst., 195, 475-529	V	25°C/2000-12000 bars	Dio
Cameron & others, 1973, Am. Min., 58, 594-618	V	24-1000°C/1 atm	Dio
Clark & others, 1962, Carn. Inst. Wash. Yb., 59-68	V	25°C/1 atm	Dio
Rigby & others, 1942, Trans. Brit. Ceram. Soc., 41, 123-143	V	100-1200°C/1 atm	Dio
Sakata, 1957, Japan. J. Geol. Geog., 28, 161-168	V	25°C/1 atm	Dio
Wones & Dodge, 1977, Thermo. in Geol., 229-247	V	25°C/1 atm	Dio
Newton & others, 1977, Geochim. Cosmo. Acta, 41, 369-377	dH/dX	970 K/1 atm	Dio+Cts($CaMgSi_2O_6$-$CaAl_2SiO_6$ join)
Davis & Boyd, 1966, JGR, 71, 3567-3576	a	900-1675°C/30000 bars	Dio+Ens($MgSiO_3$-$CaMgSi_2O_6$ join)
Mori & Green, 1975, Earth Plant. Sci. Lett., 26, 277-286	a	1100-1700°C/30000 bars	Dio+Ens($MgSiO_3$-$CaMgSi_2O_6$ join)
Nehru & Wyllie, 1974, Cont. Min. Pet., 48, 221-228	a	1000-1500°C/30000 bars	Dio+Ens($MgSiO_3$-$CaMgSi_2O_6$ join)
Warner & Luth, 1974, Am. Min., 59, 98-109	a	900-1300°C/2000-10000 bars	Dio+Ens($MgSiO_3$-$CaMgSi_2O_6$ join)
Newton & others, 1977, Geochim. Cosmo. Acta, 41, 369-377	dV/dX	25°C/1 atm	Dio+Cts($CaMgSi_2O_6$-$CaAl_2SiO_6$ join)

Dolomite $CaMg(CO_3)_2$ Dol

Minor solid solution

(Mg,Ca) Dolomite - Calcite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Krupka & others, 1977, GSA Abs. Prog., 9, 1060; Krupka, unpubl.	Cp	350-800 K/1 atm	Dol
Stout & Robie, 1963, J. Phys. Chem., 67, 2248-2252	Cp	11-300 K/1 atm	Dol
Stout & Robie, 1963, J. Phys. Chem., 67, 2248-2252	S	278.15 K/1 atm	Dol
Robie & Hemingway, 1977, unpubl.	H	25°C/1 atm	Dol
Goldsmith & Newton, 1969, AJS, 257-A, 160-190	G	400-720°C/9000-22000 bars	Mcc+Dol=Ara+Dol
Gordon & Greenwood, 1970, AJS, 268, 225-242	G	410-522°C/2000 bars	$Dol+Qza=Mcc+Tlc+CO_2$
Gordon & Greenwood, 1970, AJS, 268, 225-242	G	450-519°C/2000 bars	$Dol+Qza=Mcc+Tlc+CO_2$
Harker & Tuttle, 1955, AJS, 253, 209-224	G	700-950°C/300-2500 bars	$Dol=Per+Mcc+CO_2$
Metz & Winkler, 1963, Geochim. Cosmo. Acta, 27, 431-457	G	440-510°C/2000 bars	$Dol+Qza=Mcc+Tlc+CO_2$
Metz, 1967, Geochim. Cosmo. Acta, 31, 1517-1532	G	450-550°C/500-1000 bars	$Tre+Dol=For+Mcc+CO_2+H_2O$
Widmark, 1980, Cont. Min. Pet., 72, 175-179	G	547-640°C/1000-3000 bars	$Cln+Dol=Spl+For+Mcc+CO_2+H_2O$
Graf, 1961, Am. Min., 46, 1283-1316	V	25°C/1 atm	Dol
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	a	400-720°C/1900-21000 bars	Mcc+Dol($CaCO_3$-$MgCO_3$ join)
Graf & Goldsmith, 1958, Geochim. Cosmo. Acta, 13, 218-219	a	575-796°C/10000 PSI	Mcc+Dol($CaCO_3$-$MgCO_3$ join)
Harker & Tuttle, 1955, AJS, 253, 274-282	a	500-9000°C/1379-3103 bars	Mag+Dol($MgCO_3$-$CaCO_3$ join)
Harker & Tuttle, 1955, AJS, 253, 274-282	a	500-900°C/1379-3103 bars	Mcc+Dol($CaCO_3$-$MgCO_3$ join)
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	dV/dX	25°C/1 atm	Mcc+Dol($CaCO_3$-$MgCO_3$ join)

Enstatite $MgSiO_3$ - Pyroxene group; trimorph with Clinoenstatite, Protoenstatite

Important solid solution

(Mg,Fe)	Enstatite - Ferrosilite join
(MgSi,Al_2)	Enstatite - $MgAl_2SiO_6$(Mg-Al pyroxene) join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Charlu & others, 1975, Geochim. Cosmo. Acta, 39, 1487-1497	H	970 K/1 atm	Ens=Per+Qzb
Shearer & Kleppa, 1973, J. Inorg. Nuc. Chem., 35, 1073-1078	H	965-1173 K/1 atm	Ens=Per+Qzb
Atlas, 1952, J. Geol., 60, 125-147	G	975-995°C/1 atm	Ens=Pen
Boyd & Engl&, 1965, Carn. Inst. Wash. Yb., 117-123	G	620-760°C/5000-40000 bars	Ens=Cen
Boyd & others, 1964, JGR, 69, 2101-2109	G	1550°C/6100-7400 bars	Ens=Pen
Boyd, 1959, Res. Geochem., 1, 377-396	G	800-880°C/575-2000 bars	Tre=Dio+Ens+Qza+H_2O
Chernosky & Autio, 1979, Am. Min., 64, 294-303	G	664-775°C/500-2000 bars	Ant=Ens+Qzb+H_2O
Chernosky, 1976, Am. Min., 61, 1145-1155	G	600-706°C/500-4000 bars	Tlc+For=Ens+H_2O
Chernosky, 1976, Am. Min., 61, 1145-1155	G	648-744°C/500-2000 bars	Tlc=Ens+Qza+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	662-712°C/2000-2600 bars	Tlc+For=Ens+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	695-711°C/2000 bars	Ant+For=Ens+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	703-775°C/2000-2600 bars	Tlc=Ens+Qzb+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	750-775°C/2000-2600 bars	Ant=Ens+Qzb+H_2O
Haselton & others, 1978, Geophys. Res. Lett., 5, 753-756	G	1000-1500°C/20000-40000 bars	Mag+Ens=For+CO_2
Hemley & others, 1977, AJS, 277, 353-383	G	649-690°C/1000 bars	Ens+Hsi=Tlc+H_2O
Hemley & others, 1977, AJS, 277, 353-383	G	660-715°C/1000 bars	Ens+Hsi=Ant+H_2O
Hemley & others, 1977, AJS, 277, 353-383	G	680-720°C/1000 bars	For+Hsi=Ens+H_2O
Hensen & Essene, 1971, Cont. Min. Pet., 30, 72-83	G	1000-1400°C/14400-19800 bars	Ens+Sil=Pyp+Qza
Johannes, 1969, AJS, 267, 1083-1104	G	204-210°C/2000 bars	For+CO_2=Ens+Mag
Newton & Sharp, 1975, Earth Planet. Sci. Lett., 26, 239-244	G	1000-1500°C/19000-20000 bars	Mag+Ens=For+CO_2

Sarver & Hummel, 1962, J. Am. Chem. Soc., 45, 152-156	G	1039-1045°C/1 atm	Ens=Pen
Sarver & Hummel, 1962, J. Am. Chem. Soc., 45, 152-156	G	860-870°C/1 atm	Ens=Cen
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	825-890°C/11000-18000 bars	Cln=Ens+For+Spl+H_2O
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	900-970°C/20000-21000 bars	Pyp+For=Ens+Spl
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	726-774°C/400 bars	Tre=Dio+Ens+Qza+H_2O
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	830-840°C/400-500 bars	Phl+Qzb=San+Ens+H_2O
Wood, 1976, Prog. Exp. Pet., Ser. D(6-1976), 17-19	G	750-790°C/300-470 bars	Phl+Qzb=San+Ens+H_2O
Adams & Williamson, 1923, J. Franklin Inst., 195, 475-529	V	25°C/1960-12000 bars	Ens
Chernosky & Autio, 1979, Am. Min., 64, 294-303	V	25°C/1 atm	Ens
Hess, 1952, AJS, Bowen Vol., 173-187	V	25°C/1 atm	Ens
Ralph & Ghose, 1980, EOS, 61, 409	V	25°C/1-21000 bars	Ens
Sarver & Hummel, 1962, J. Am. Chem. Soc., 45, 152-156	V	200-800°C/1 atm	Ens
Stephenson & others, 1966, Min. Mag., 35, 838-846	V	26°C/1 atm	Ens
Swanson & others, 1956, US NBS Circ. 539, 6, 62 p	V	25°C/1 atm	Ens
Wones & Dodge, 1977, Thermo. in Geol., 229-247	V	25°C/1 atm	Ens
Sahama & Torgeson, 1949, US Bur. Mines Rpt. Inv. 4408	dH/dX	73.7°C/1 atm	Ens+Fes($MgSiO_3$-$FeSiO_3$ join)
Davis & Boyd, 1966, JGR, 71, 3567-3576	a	900-1675°C/30000 bars	Dio+Ens($MgSiO_3$-$CaMgSi_2O_6$ join)
Mori & Green, 1975, Earth Plant. Sci. Lett., 26, 277-286	a	1100-1700°C/30000 bars	Dio+Ens($MgSiO_3$-$CaMgSi_2O_6$ join)
Nehru & Wyllie, 1974, Cont. Min. Pet., 48, 221-228	a	1000-1500°C/30000 bars	Dio+Ens($MgSiO_3$-$CaMgSi_2O_6$ join)
Warner & Luth, 1974, Am. Min., 59, 98-109	a	900-1300°C/2000-10000 bars	Dio+Ens($MgSiO_3$-$CaMgSi_2O_6$ join)

Epidote $Ca_2FeAl_2Si_3O_{12}(OH)$ - Epidote group

Important solid solution

(Fe^{+3},Al) Epidote - Zoisite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Kiseleva & others, 1974, Geokhim., 4, 543-553	H_T-H_R	335-1100 K/1 atm	Ept
Liou, 1973, J. Pet., 14, 381-413	G	630-762°C/2000-5000 bars	Ept+Mgt=(Gro+Adr+Alm)+Ano+Qza+Hem+H_2O
Liou, 1973, J. Pet., 14, 381-413	V	25°C/1 atm	Ept

Epistilbite $CaAl_2Si_6O_{16}\cdot 5H_2O$ - Zeolite group

Reference	Data type	Range (Temperature/pressure)	Phases studied
Lo, 1978, Proc. Geol. Soc. China, 21, 25-33	G	258-308°C/690-2069 bars	$Epi=Wai+Qza+H_2O$
Liou, 1970, Cont. Min. Pet., 27, 259-282	V	25°C/1 atm	Epi

Fayalite Fe_2SiO_4 - Olivine group

Important solid solution

(Fe,Mg) Fayalite - Forsterite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Robie & others, unpubl.	Cp		Fay
Orr, 1953, J. Am. Chem. Soc., 75, 528-529	H_T-H_R	298-1724 K/1 atm	Fay
Kelley & King, 1961, US Bur. Mines Bull. 592, 149 p	S	298.15 K/1 atm	Fay
Robie & others, unpubl.	S	298.15 K/1 atm	Fay
King, 1952, J. Am. Chem. Soc., 74, 4446-4448	H		Fay
Bohlen & others, 1980, Earth Planet. Sci. Lett., 47, 1-10	G	700-850°C/10500-12000 bars	Fes=Fay+Qza
Bohlen & others, 1980, Earth Planet. Sci. Lett., 47, 1-10	G	900-1050°C/12500-15000 bars	Fes=Fay+Qzb
Chou, 1978, Am. Min., 63, 690-703	G	600-800°C/2000-4000 bars	Mgt+Qzb=Fay+Oxy
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	540-550°C/1035 bars	Ann+Qzb+Irn=San+Fay+Wus+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	650-710°C/1035-2070 bars	Ann+Qzb=Mag+San+Fay+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	760-765°C/1035 bars	Ann=Leu+Kal+Fay+Irn+Wus+H_2O
Gustafson, 1974, J. Pet., 15, 455-496	G	748-797°C/500-2000 bars	Adr+Fay=Mag+Wol+Qzb
Hewitt, 1976, EOS, 57, 1020	G	650-850°C/1000 bars	Mgt+Qzb=Fay+Oxy
Lindsley, 1965, Carn. Inst. Wash. Yb., 148-150	G	1000-1100°C/15500-17000 bars	Fes=Fay+Qza
Lindsley, 1965, Carn. Inst. Wash. Yb., 148-150	G	1275-1280°C/1700-1750 bars	Pfs=Fay+Qza
Liou, 1974, Am. Min., 59, 1016-1025	G	570-610°C/500-2000 bars	Adr+Qza+Fay=Hed+Wol
Smith, 1971, AJS, 271, 370-382	G	1075-1100°C/15500-18000 bars	Fes=Fay+Qzb
Smith, 1971, AJS, 271, 370-382	G	750-900°C/11000-15000 bars	Fes=Fay+Qza
Taylor & Schmalzried, 1964, J. Phys. Chem., 68, 2444-2449	G	900-1100°C/1 atm	Fay
Wones & Gilbert, 1969, AJS, 267-A, 480-488	G	594-803°C/800-2000 bars	Mgt+Qzb=Fay+Oxy
Hazen, 1977, Am. Min., 62, 286-295	V	-196-23°C/1-42000 bars	Fay
Rigby & others, 1946, Trans. Brit. Ceram. Soc., 45, 237-250	V	100-1000°C/1 atm	Fay
Smith, 1975, Am. Min., 60, 1092-1097	V	20-900°C/1 atm	Fay

Ferrosilite $FeSiO_3$ - Pyroxene group

Important solid solution

(Fe,Mg) Ferrosilite - Enstatite join

(FeSi,Al_2) Ferrosilite - $FeAl_2SiO_6$ (Fe-Al Pyroxene) join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Bohlen & others, 1980, Earth Planet. Sci. Lett., 47, 1-10	G	700-850°C/10500-12000 bars	Fes=Fay+Qza
Bohlen & others, 1980, Earth Planet. Sci. Lett., 47, 1-10	G	900-1050°C/12500-15000 bars	Fes=Fay+Qzb
Lindsley, 1965, Carn. Inst. Wash. Yb., 148-150	G	1000-1100°C/15500-17000 bars	Fes=Fay+Qza
Lindsley, 1965, Carn. Inst. Wash. Yb., 148-150	G	1100-1425°C/20000-45000 bars	Fes=Pfs
Lindsley, 1965, Carn. Inst. Wash. Yb., 148-150	G	775-825°C/10000-40000 bars	Cfs=Fes
Smith, 1971, AJS, 271, 370-382	G	1075-1100°C/15500-18000 bars	Fes=Fay+Qzb
Smith, 1971, AJS, 271, 370-382	G	750-900°C/11000-15000 bars	Fes=Fay+Qza
Burnham, 1965, Carn. Inst. Wash. Yb., 202-204	V	25°C/1 atm	Fes
Sahama & Torgeson, 1949, US Bur. Mines Rpt. Inv. 4408	dH/dX	73.7°C/1 atm	Ens+Fes($MgSiO_3$-$FeSiO_3$ join)
Lindsley & Munoz, 1969, AJS, 267-A, 295-324	a	730-1000°C/20000 bars	Fes+Hed($FeSiO_3$-$CaFeSi_2O_6$ join)

Forsterite Mg_2SiO_4 - Olivine group

Important solid solution

(Mg,Fe) Forsterite - Fayalite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Orr, 1953, J. Am. Chem. Soc., 75, 528-529	H_T-H_R	298-1808 K/1 atm	For
Kelley & King, 1961, US Bur. Mines Bull. 592, 149 p	S	298.15 K/1 atm	For
Charlu & others, 1975, Geochim. Cosmo. Acta, 39, 1487-1497	H	970 K/1 atm	For
King & others, 1967, US Bur. Mines Rpt. Inv. 6962, 19 p	H	25°C/1 atm	For=Per+Qza
Shearer & Kleppa, 1973, J. Inorg. Nuc. Chem., 35, 1073-1078	H	965-1173 K/1 atm	For+Per+Qzb
Chernosky, 1974, Am. Min., 59, 496-507	G	576-750°C/500-3000 bars	$Cln=For+Spl+Crd+H_2O$
Chernosky, 1976, Am. Min., 61, 1145-1155	G	600-706°C/500-4000 bars	$Tlc+For=Ens+H_2O$
Evans & others, 1976, Schweig. Min. Pet. Mitt., 56, 79-93	G	480-660°C/2000-15000 bars	$Atg=For+Tlc+H_2O$
Greenwood, 1963, J. Pet., 4, 317-351	G	662-712°C/2000-2600 bars	$Tlc+For=Ens+H_2O$
Greenwood, 1963, J. Pet., 4, 317-351	G	663-679°C/1000-4000 bars	$For+Tlc=Ant+H_2O$
Greenwood, 1963, J. Pet., 4, 317-351	G	695-711°C/2000 bars	$Ant+For=Ens+H_2O$
Haselton & others, 1978, Geophys. Res. Lett., 5, 753-756	G	1000-1500°C/20000-40000 bars	$Mag+Ens=For+CO_2$
Hemley & others, 1977, AJS, 277, 322-351	G	450-600°C/1000 bars	$For+Hsi=Tlc+H_2O$
Hemley & others, 1977, AJS, 277, 353-383	G	550-640°C/1000 bars	$For+Hsi=Tlc+H_2O$
Hemley & others, 1977, AJS, 277, 353-383	G	650-670°C/1000 bars	$Ant+H_2O=For+Hsi$
Hemley & others, 1977, AJS, 277, 353-383	G	680-720°C/1000 bars	$For+Hsi=Ens+H_2O$
Johannes, 1968, Cont. Min. Pet., 19, 309-315	G	330-440°C/500-7000 bars	$Chr+Bru=For+H_2O$
Johannes, 1969, AJS, 267, 1083-1104	G	204-210°C/2000 bars	$For+CO_2=Ens+Mag$
Johannes, 1969, AJS, 267, 1083-1104	G	450-660°C/500-7000 bars	$For+H_2O+CO_2=Tlc+Mag$
Metz, 1967, Geochim. Cosmo. Acta, 31, 1517-1532	G	450-550°C/500-1000 bars	$Tre+Dol=For+Mcc+CO_2+H_2O$
Newton & Sharp, 1975, Earth Planet. Sci. Lett., 26, 239-244	G	1000-1500°C/19000-20000 bars	$Mag+Ens=For+CO_2$

Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	825-890°C/11000-18000 bars	Cln=Ens+For+Spl+H_2O
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	870-900°C/22000-35000 bars	Cln=Pyp+For+Spl+H_2O
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	900-970°C/20000-21000 bars	Pyp+For=Ens+Spl
Widmark, 1980, Cont. Min. Pet., 72, 175-179	G	547-640°C/1000-3000 bars	Cln+Dol=Spl+For+Mcc+CO_2+H_2O
Wones, 1967, Geochim. Cosmo. Acta, 31, 2248-2253	G	902-1018°C/100-400 bars	Phl=Kal+Leu+For+H_2O
Hazen, 1976, Am. Min., 61, 1280-1293	V	-196-1020°C/1-50000 bars	For
Kozu & others, 1934, Proc. Imp. Acad. Japan, 10, 83-86	V	20-1000°C/1 atm	For
Olinger & Halleck, 1974, JGR, 79, 5535-5536	V	25°C/1-108500 bars	For
Rigby & others, 1942, Trans. Brit. Ceram. Soc.; 41, 123-143	V	100-1200°C/1 atm	For
Skinner, 1962, USGS Prof. Paper 450-D, 109-112	V	25-1127°C/1 atm	For
Wones, 1967, Geochim. Cosmo. Acta, 31, 2248-2253	V	25°C/1 atm	For
Finnerty & Boyd, 1978, Carn. Inst. Wash. Yb., 713-717	a	1000-1400°C/10000-50000 bars	For+Col(Mg_2SiO_4-Ca_2SiO_4 join)
Warner & Luth, 1973, Am. Min., 58, 998-1008	a		For+Col(Mg_2SiO_4-Ca_2SiO_4 join)

Gibbsite $Al(OH)_3$ Gib

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemingway & others, 1977, USGS J. Res., 5, 797-806	Cp	200-480 K/1 atm	Gib
Hemingway & others, 1977, USGS J. Res., 5, 797-806	S	298.15 K/1 atm	Gib
Barany & Kelley, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	H	346.85 K/1 atm	Hal+H_2O=Qza+Gib
Barany & Kelley, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	H	346.85 K/1 atm	Kao+H_2O=Qza+Gib
Hemingway & Robie, 1977, USGS J. Res., 5, 413-429	H	303.4 K/1 atm	Alu+H_2O=Gib+Hyd
Kracek & Neuvonen, 1952, AJS, Bowen Vol., 293-318	H	347.85 K/1 atm	Ano+H_2O=Lme+Gib+Qza
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Gib

Graphite C - dimorph with Diamond

Reference	Data type	Range (Temperature/pressure)	Phases studied
JANAF, 1978	Cp	298-6000 K/1 atm	Gra
JANAF, 1978	S	298-6000 K/1 atm	Gra
Nelson & Riley, 1945, Phys. Soc. London Proc., 57, 477-495	V	15-800°C/1 atm	Gra

Grossular $Ca_3Al_2Si_3O_{12}$ - Garnet group

Important solid solution

(Al^{+3},Fe^{+3})	Grossular - Andradite join

Minor solid solution

(Ca,Fe)	Grossular - Almandine join
(Ca,Mg)	Grossular - Pyrope join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Haselton & Westrum, 1980, Geochim. Cosmo. Acta, 44, 701-709	Cp	11-343 K/1 atm	Gro
Kolesnik & others, 1979, Geokhim., 713-721	Cp	14-296 K/1 atm	Gro
Krupka & others, 1979, Am. Min., 64, 86-101	Cp	350-978 K/1 atm	Gro
Westrum & others, 1979, J. Chem. Thermodyn., 11, 57-66	Cp	200-596 K/1 atm	Gro
Haselton & Westrum, 1980, Geochim. Cosmo. Acta, 44, 701-709.	S	298.15 K/1 atm	Gro
Westrum & others, 1979, J. Chem. Thermodyn., 11, 57-66	S	298.15 K/1 atm	Gro
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Gro=Lme+Cor+Qzb
Boettcher, 1970, J. Pet., 11, 337-379	G	1033-1053 K/1000 bars	Ano+Geh=Gro+Cor
Boettcher, 1970, J. Pet., 11, 337-379	G	853-933 K/4000-5300 bars	Gro+Ano+H_2O=Zoi+Qza
Boettcher, 1970, J. Pet., 11, 337-379	G	893-1053 K/3000-5900 bars	Ano+Wol=Gro+Qzb
Boettcher, 1970, J. Pet., 11, 337-379	G	898-928 K/3000 bars	Gro+Ano+Cor+H_2O=Zoi
Goldsmith, 1980, Am. Min., 65, 272-284	G	1100-1400°C/22000-31000 bars	Ano=Gro+Kya+Qza
Gordon & Greenwood, 1971, Am. Min., 56, 1674-1688	G	700-849°C/2000 bars	Ccl+Ano+Wol=Gro+CO_2
Hays, 1965, Carn. Inst. Wash. Yb., 234-239	G	1473-1523 K/11000-14600 bars	Gro=Ano+Wol+Geh
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	715-825°C/1000-4000 bars	Ano+Ccl=Gro+Cor+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	715-825°C/1000-4000 bars	Gro+Cor+Ccl=Geh+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	725-825°C/1000 bars	Ano+Ccl=Geh+Gro+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	725-825°C/1000-4000 bars	Ano+Wol+Ccl=Gro+CO_2

Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	755-788°C/1000 bars	Gro+Ccl=Geh+Wol+CO_2
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	1028-1263 K/1000-6000 bars	Ano+Geh=Gro+Cor
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	1125-1423 K/200-10000 bars	Gro=Ano+Wol+Geh
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	848-858 K/1000-3000 bars	Ano+Wol=Gro+Qza
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	888-958 K/4000 bars	Ano+Wol=Gro+Qzb
Liou, 1973, J. Pet., 14, 381-413	G	630-762°C/2000-5000 bars	Ept+Mgt=(Gro+Adr+Alm)+Ano+Qza+Hem+H_2O
Newton, 1965, J. Geol., 73, 431-441	G	843-1113 K/2000-6800 bars	Gro+Ano+Cor+H_2O=Zoi
Newton, 1966, AJS, 264, 204-222	G	803-923 K/1100-2000 bars	Ano+Wol=Gro+Qza
Newton, 1966, AJS, 264, 204-222	G	973-1023 K/4700-5700 bars	Ano+Wol=Gro+Qzb
Shmulovich, 1974, Geochem. Int., 11, 883-887	G	1133-1153 K/500-700 atm	Gro=Ano+Wol+Geh
Shmulovich, 1977, Geochem. Int., 14, 126-134	G	627-727°C/1000-3920 bars	Ccl+Wol+Ano=Gro+CO_2
Strens, 1968, Min. Mag., 36, 864-867	G	770-823 K/2000 bars	Gro+Ano+H_2O=Zoi+Qza
Adams & Gibson, 1929, Proc. Nat. Acad. Sci., 15, 713-724	V	25°C/2000-12000 bars	Gro
Hazen & Finger, 1978, Am. Min., 63, 297-303	V	25°C/1-61000 bars	Gro
Lieberman & Gandall, 1952, J. Am. Ceram. Soc., 35, 304-308	V	293-343 K/1 atm	Gro
Meagher, 1975, Am. Min., 60, 218-228	V	25-675°C/1 atm	Gro
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Gro
Vaidya & others, 1973, JGR, 78, 6893-6898	V	25°C/5000-45000 bars	Gro
Newton & others, 1977, Geochim. Cosmo. Acta, 41, 369-377	dH/dX	970 K/1 atm	Gro+Pyp($Ca_3Al_2Si_3O_{12}$-$Mg_3Al_2Si_3O_{12}$ join)
Cressy & others, 1978, Cont. Min. Pet., 67, 397-404	a.	850-1100°C/10000-22700 bars	Gro+Alm($Ca_3Al_2Si_3O_{12}$-$Fe_3Al_2Si_3O_{12}$ join)
Cressy & others, 1978, Cont. Min. Pet., 67, 397-404	dV/dX	25°C/1 atm	Gro+Alm($Ca_3Al_2Si_3O_{12}$-$Fe_3Al_2Si_3O_{12}$ join)
Newton & others, 1977, Geochim. Cosmo. Acta, 41, 369-377	dV/dX	25°C/1 atm	Gro+Pyp($Ca_3Al_2Si_3O_{12}$-$Mg_3Al_2Si_3O_{12}$ join)

Halloysite $Al_2Si_2O_5(OH)_4$ - Clay group; trimorph with Kaolinite, Dickite Hal

Reference	Data type	Range (Temperature/pressure)	Phases studied
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	Cp	206-296 K/1 atm	Hal
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	S	298.15 K/1 atm	Hal
Barany & Kelley, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	H	346.85 K/1 atm	Hal+H_2O=Qza+Gib

Hedenbergite $CaFeSi_2O_6$ - Pyroxene group

Important solid solution

(Fe,Mg)	Hedenbergite - Diopside join
$(FeSi,Al_2)$	Hedenbergite - Ca-Al Clinopyroxene join
(Ca,Fe)	Hedenbergite - Clinoferrosilite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Gustafson, 1974, J. Pet., 15, 455-496	G	401-529°C/2000 bars	Hed+Bun=Adr+Mag+Qzb+Nic
Liou, 1974, Am. Min., 59, 1016-1025	G	570-610°C/500-2000 bars	Adr+Qza+Fay=Hed+Wol
Liou, 1974, Am. Min., 59, 1016-1025	G	621-683°C/500-2000 bars	Adr+Qza+Nic=Hed+Wol+Bun
Cameron & others, 1973, Am. Min., 58, 594-618	V	24-1000°C/1 atm	Hed
Gustafson, 1974, J. Pet., 15, 455-496	V	25°C/1 atm	Hed
Kuno & Hess, 1953, AJS, 251, 741-752	V	25°C/1 atm	Hed
Lindsley, 1967, Carn. Inst. Wash. Yb., 230-234	V	25°C/1 atm	Hed
Rutstein & Yund, 1969, Am. Min., 54, 238-245	V	25°C/1 atm	Hed
Vaidya & others, 1973, JGR, 78, 6893-6898	V	25°C/5000-45000 bars	Hed
Lindsley & Munoz, 1969, AJS, 267-A, 295-324	a	730-1000°C/20000 bars	Fes+Hed($FeSiO_3$-$CaFeSi_2O_6$ join)
Rutstein, 1971, Am. Min., 56, 2040-2052	a	600-1000°C/1000 bars	Wol+Hed($CaSiO_3$-$CaFeSi_2O_6$ join)

Hematite Fe_2O_3 Hem

Reference	Data type	Range (Temperature/pressure)	Phases studied
Gronvold & Samuelsen, 1975, J. Phys. Chem., 36, 249-256	Cp	302-1054 K/1 atm	Hem
Gronvold & Westrum, 1959, J. Am. Chem. Soc., 81, 1780-1783	Cp	5.5-345 K/1 atm	Hem
Reznitskii & Filippova, 1972, Neorg. Mater., 8, 481-484	Cp	298-1000 K/1 atm	Hem
Coughlin & others, 1951, J. Am. Chem. Soc., 73, 3891-3893	H_T-H_R	375-1757 K/1 atm	Hem
Gronvold & Westrum, 1959, J. Am. Chem. Soc., 81, 1780-1783	S	298.15 K/1 atm	Hem
Komarov & others, 1967, Neorg. Mater., 3, 1064-1072	G(emf)	1273-1657 K/1 atm	Mag+Oxy=Hem
Liou, 1973, J. Pet., 14, 381-413	G	630-762°C/2000-5000 bars	Ept+Mgt=(Gro+Adr+Alm)+Ano+Qza+Hem+H_2O
Rau, 1972, J. Chem. Thermodyn., 4, 57-64	G	767-840 K/1 atm	Hem+Hyd=Mag+H_2O
Schmahl, 1941, Z. Electrochem., 47, 821-843	G	1583-1683 K/1 atm	Mag+Oxy=Hem
Taylor & Liou, 1978, Am. Min., 63, 378-393	G	498-600°C/2000 bars	Qza+Ccl+Hem=Adr+CO_2
Tret'yakov & Khomyakov, 1962, Russ. J. Inorg. Chem., 7, 628-631	G	1373-1728 K/1 atm	Mag+Oxy=Hem
Gorton & others, 1965, Trans. Metal. Soc. AIME, 233, 1519-1525	V	273-1270 K/1 atm	Hem
Sharma, 1950, Proc. Indian Acad. Sci., A32, 285-291	V	320-670 K/1 atm	Hem

Heulandite $CaAl_2Si_7O_{18}\cdot 6H_2O$ - Zeolite group

Important solid solution

(Ca,Na_2)	Heulandite - $Na_2Al_2Si_7O_{18}\cdot 6H_2O$ join
$(CaSi,NaAl)$	Heulandite - $NaAl_3Si_6O_{18}\cdot 6H_2O$ join
$(H_2O,[])$	Heulandite - $CaAl_2Si_7O_{18}\cdot 6[]$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Nitsch, 1968, Naturw., <u>55</u>, 388	G	160-210°C/7000 bars	$Heu=Law+Qza+H_2O$
Alberti, 1972, Tsch. Min. Pet. Mitt., <u>18</u>, 129-146	V	25°C/1 atm	Heu
Miller & Ghent, 1973, Can. Min., <u>12</u>, 188-192	V	25°C/1 atm	Heu

Illite $(K,H_3O)_{x+y}(Mg,Fe)_xAl_{2-x+y}Si_{4-y}O_{10}(OH)_2\cdot(1-x-y-z)H_2O$* - Clay/Mica group Ill

$x+y+z \leq 1$

Generalized end-member components

$Al_2Si_4O_{10}(OH)_2\cdot H_2O$ - $Al_2Si_4O_{10}(OH)_2$

$KAl_3Si_3O_{10}(OH)_2$ - $(H_3O)Al_3Si_3O_{10}(OH)_2$

$KAl(Mg,Fe)Si_4O_{10}(OH)_2$ - $(H_3O)Al(Mg,Fe)Si_4O_{10}(OH)_2$

* Composition of sample studied for Cp, S: $K_{.75}Mg_{.25}Al_{2.25}Si_{3.5}O_{10}(OH)_2$ $X = .25,\ y = .5,\ z = .25$

Reference	Data type	Range (Temperature/pressure)	Phases studied
Robie & others, 1976, USGS J. Res., 4, 631-644	Cp	15-380 K/1 atm	Ill
Robie & others, 1976, USGS J. Res., 4, 631-644	S	298.15 K/1 atm	Ill

Kaolinite $Al_2Si_2O_5(OH)$ - Clay group; trimorph with Dickite, Halloysite

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemingway & others, 1978, Geochim. Cosmo. Acta, 42, 1533-1543	Cp	340-800 K/1 atm	Kao
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	Cp	206-296 K/1 atm	Kao
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	S	298.15 K/1 atm	Kao
Barany & Kelley, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	H	346.85 K/1 atm	Kao+H_2O=Qza+Gib
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Boe+Qza+H_2O=Kao
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Dia+Qza+H_2O=Kao
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Kao+Qza=Pyr+H_2O
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Kao

Kyanite — Al_2SiO_5 - trimorph with Andalusite, Sillimanite

Reference	Data type	Range (Temperature/pressure)	Phases studied
Todd, 1950, J. Am. Chem. Soc., 72, 4742-4743	Cp	206-296 K/1 atm	Kya
Pankratz & Kelley, 1964, US Bur. Mines Rpt. Inv. 6555, 7 p	H_T-H_R	390-1503 K/1 atm	Kya
Todd, 1950, J. Am. Chem. Soc., 72, 4742-4743	S	298.15 K/1 atm	Kya
Anderson & Kleppa, 1969, AJS, 267, 285-290	H	974 K/1 atm	Kya=Cor+Qza
Bird & Fawcett, 1973, J. Pet., 14, 415-428	G	634-664°C/8270-9790 bars	Cln+Mus=Phl+Kya+Qza+H_2O
Chatterjee, 1972, Cont. Min. Pet., 34, 288-303	G	570-640°C/5000-7000 bars	Par+Qza=Ana+Kya+H_2O
Essene & others, 1972, EOS, 53, 544	G	800-1200°C/18500-29000 bars	Jad+Kya=Ana+Cor
Goldsmith, 1980, Am. Min., 65, 272-284	G	1100-1400°C/22000-31000 bars	Ano=Gro+Kya+Qza
Holdaway, 1971, AJS, 271, 97-131	G	650-858 K/2400-4800 bars	Kya=And
Holland, 1979, Cont. Min. Pet., 68, 293-301	G	550-700°C/23000-26000 bars	Par=Jad+Kya+H_2O
Newton, 1966, Sci., 153, 170-172	G	973-1123 K/6100-7400 bars	Kya=And
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	340-385°C/4000-5000 bars	Law=Zoi+Kya+Pyr+H_2O
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	803-933 K/4000-5000 bars	Ano+Kya+H_2O=Mar+Qza
Brace & others, 1969, JGR, 74, 2089-2098	V	25°C/1000-40000 bars	Kya
Skinner & others, 1961, AJS, 259, 651-668	V	25-1055°C/1 atm	Kya
Winter & Ghose, 1979, Am. Min., 64, 573-586	V	25-800°C/1 atm	Kya

Laumontite $CaAl_2Si_4O_{12}\cdot 4H_2O$ - Zeolite group

Important solid solution

(H_2O,[]) Laumontite - $CaAl_2Si_4O_{12}\cdot 4[]$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Juan & Lo, 1971, Proc. Geol. Soc. China, 14, 34-44	G	250-278°C/890-1380 bars	Lau=Wai+H_2O
Liou, 1971, Cont. Min. Pet., 31, 171-177	G	175-200°C/3000-5000 bars	Stl=Lau+Qza+H_2O
Liou, 1971, J. Pet., 12, 379-411	G	194-249°C/2800-3500 bars	Lau=Law+Qza+H_2O
Liou, 1971, J. Pet., 12, 379-411	G	259-330°C/1000-6000 bars	Lau=Wai+H_2O
Nitsch, 1968, Naturw., 55, 388	G	345°C/2500-3500 bars	Lau=Law+Qza+H_2O
Thompson, 1970, AJS, 269, 267-275	G	250°C/2500-3000 bars	Lau=Law+Qza+H_2O
Thompson, 1970, AJS, 269, 267-275	G	300-357°C/1000-6000 bars	Lau=Ano+Qza+H_2O
Liou, 1971, J. Pet., 12, 379-411	V	25°C/1 atm	Lau

Lawsonite $CaAl_2Si_2O_7(OH)_2 \cdot H_2O$ Law

Reference	Data type	Range (Temperature/pressure)	Phases studied
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5855, 8 p	Cp	53-296 K/1 atm	Law
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5855, 8 p	S	298.15 K/1 atm	Law
Barany, 1962, US Bur. Mines Rpt. Inv. 5900, 17 p	H	73.7°C/1 atm	Law
Crawford & Fyfe, 1965, AJS, 263, 262-270	G	350-515°C/5170-8900 bars	Law=Ano+H_2O
Liou, 1971, J. Pet., 12, 379-411	G	194-249°C/2800-3500 bars	Lau=Law+Qza+H_2O
Liou, 1971, J. Pet., 12, 379-411	G	297-381°C/3200-4350 bars	Wai=Law+Qza
Nitsch, 1968, Naturw., 55, 388	G	160-210°C/7000 bars	Heu=Law+Qza+H_2O
Nitsch, 1968, Naturw., 55, 388	G	345°C/2500-3500 bars	Lau=Law+Qza+H_2O
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	310-390°C/4000-7000 bars	Ccl+Pyr+H_2O=Law+Qza+CO_2
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	340-385°C/4000-5000 bars	Law=Zoi+Kya+Pyr+H_2O
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	370-430°C/7000 bars	Law+Qza=Zoi+Pyr+H_2O
Nitsch, 1974, For. Min., 51, 34-35	G	325-445°C/4000-10000 bars	Law=Zoi+Mar+Qza+H_2O
Thompson, 1970, AJS, 269, 267-275	G	250°C/2500-3000 bars	Lau=Law+Qza+H_2O
Baur, 1978, Am. Min., 63, 311-315	V	25°C/1 atm	Law
Pabst, 1961, Z. Krist., 116, 210-219	V		Law
Pistorius, 1961, Am. Min., 46, 982-985	V	25°C/1 atm	Law

Leonhardite $Ca_2Al_4Si_8O_{24} \cdot 7H_2O$ - Zeolite group

Important solid solution

(H_2O,[]) Leonhardite - $Ca_2Al_4Si_8O_{24} \cdot 7[]$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5855, 8 p	Cp	53-296 K/1 atm	Leo
King & Weller, 1961, US Bur. Mines Rpt. Inv. 5855, 8 p	S	298.15 K/1 atm	Leo

Magnesite $MgCO_3$

Important solid solution

(Mg,Ca) Magnesite - Dolomite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemingway & others, 1977, USGS J. Res., 5, 797-806	Cp		Mag
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	298-743 K/1 atm	Mag
Hemingway & others, 1977, USGS J. Res., 5, 797-806	S	298.15 K/1 atm	Mag
Harker & Tuttle, 1955, AJS, 253, 209-224	G	600-900°C/165-2757 bars	Mag=Per+CO_2
Harker & Tuttle, 1955, AJS, 253, 209-224	G	600-900°C/165-2758 bars	Mag=Per+CO_2
Haselton & others, 1978, Geophys. Res. Lett., 5, 753-756	G	1000-1500°C/20000-40000 bars	Mag+Ens=For+CO_2
Johannes & Metz, 1968, Neues Jahrb. Min., M., 68, 15-26	G	450-600°C/1000 bars	Mag+H_2O=Bru+CO_2
Johannes & Metz, 1968, Neues Jahrb. Min., M., 68, 15-26	G	635-800°C/500-2000 bars	Mag=Per+CO_2
Johannes & Metz, 1968, Neues Jahrb. Min., M., 68, 15-26	G	700-770°C/500-1000 bars	Mag=Per+CO_2
Johannes, 1969, AJS, 267, 1083-1104	G	204-210°C/2000 bars	For+CO_2=Ens+Mag
Johannes, 1969, AJS, 267, 1083-1104	G	300-600°C/330-7000 bars	Tlc+CO_2=Qza+Mag+H_2O
Johannes, 1969, AJS, 267, 1083-1104	G	340-490°C/1000-4000 bars	Chr+CO_2=Tlc+Mag+H_2O
Johannes, 1969, AJS, 267, 1083-1104	G	450-660°C/500-7000 bars	For+H_2O+CO_2=Tlc+Mag
Newton & Sharp, 1975, Earth Planet. Sci. Lett., 26, 239-244	G	1000-1500°C/19000-20000 bars	Mag+Ens=For+CO_2
Rau, 1972, J. Chem. Thermodyn., 4, 57-64	G	583-810 K/1 atm	Mag+Hyd=Irn+H_2O
Rau, 1972, J. Chem. Thermodyn., 4, 57-64	G	767-840 K/1 atm	Hem+Hyd=Mag+H_2O
Walter & others, 1962, J. Pet., 3, 49-64	G	463-666°C/1000-4000 bars	Mgt+H_2O=Bru+CO_2
Graf, 1961, Am. Min., 46, 1283-1316	V	25°C/1 atm	Mag
Swanson & others, 1957, US NBS Circ. 539, 7, 70 p	V	25°C/1 atm	Mag
Harker & Tuttle, 1955, AJS, 253, 274-282	a	500-9000°C/1379-3103 bars	Mag+Dol($MgCO_3$-$CaCO_3$ join)

Magnesiocalcite $Ca_{1-x}Mg_xCO_3$ - solid solution of Calcite along Calcite - Dolomite join Mcc

Reference	Data type	Range (Temperature/pressure)	Phases studied
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	G	400-720°C/9000-22000 bars	Mcc+Dol=Ara+Dol
Gordon & Greenwood, 1970, AJS, 268, 225-242	G	410-522°C/2000 bars	Dol+Qza=Mcc+Tlc+CO_2
Gordon & Greenwood, 1970, AJS, 268, 225-242	G	450-519°C/2000 bars	Dol+Qza=Mcc+Tlc+CO_2
Harker & Tuttle, 1955, AJS, 253, 209-224	G	700-950°C/300-2500 bars	Dol=Per+Mcc+CO_2
Metz & Winkler, 1963, Geochim. Cosmo. Acta, 27, 431-457	G	440-510°C/2000 bars	Dol+Qza=Mcc+Tlc+CO_2
Metz, 1967, Geochim. Cosmo. Acta, 31, 1517-1532	G	450-550°C/500-1000 bars	Tre+Dol=For+Mcc+CO_2+H_2O
Widmark, 1980, Cont. Min. Pet., 72, 175-179	G	547-640°C/1000-3000 bars	Cln+Dol=Spl+For+Mcc+CO_2+H_2O
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	a	400-720°C/1900-21000 bars	Mcc+Dol($CaCO_3$-$MgCO_3$ join)
Graf & Goldsmith, 1958, Geochim. Cosmo. Acta, 13, 218-219	a	575-796°C/10000 PSI	Mcc+Dol($CaCO_3$-$MgCO_3$ join)
Harker & Tuttle, 1955, AJS, 253, 274-282	a	500-900°C/1379-3103 bars	Mcc+Dol($CaCO_3$-$MgCO_3$ join)
Goldsmith & Newton, 1969, AJS, 267-A, 160-190	dV/dX	25°C/1 atm	Mcc+Dol($CaCO_3$-$MgCO_3$ join)

Magnetite Fe_3O_4 Mgt

Reference	Data type	Range (Temperature/pressure)	Phases studied
Gronvold & Sveen, 1974, J. Chem. Thermodyn., 6, 859-872	Cp	300-1044 K/1 atm	Mgt
Westrum & Gronvold, 1969, J. Chem. Thermodyn., 1, 543-557	Cp	6.49-348 K/1 atm	Mgt
Coughlin & others, 1951, J. Am. Chem. Soc., 73, 3891-3893	H_T-H_R	351-1825 K/1 atm	Mgt
Westrum & Gronvold, 1969, J. Chem. Thermodyn., 1, 543-557	S	298.15 K/1 atm	Mgt
Birks, 1966, Nature, 210, 407-408	G(emf)	838 K/1 atm	Wus=Irn+Mgt
Chou, 1978, Am. Min., 63, 690-703	G	600-800°C/2000-4000 bars	Mgt+Qzb=Fay+Oxy
Darken & Gurry, 1945, J. Am. Chem. Soc., 67, 1398-1412	G	1369-1661 K/1 atm	Wus+CO_2=Mgt+CO
Emmett & Schultz, 1933, J. Am. Chem. Soc., 55, 1376-1389	G	673-823 K/1 atm	Mgt+Hyd=Irn+H_2O
Emmett & Schultz, 1933, J. Am. Chem. Soc., 55, 1376-1389	G	873-1073 K/1 atm	Mgt+H_2O=Wus+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	610-640°C/1035-2070 bars	Ann+Bun=San+Mgt+Nil+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	650-710°C/1035-2070 bars	Ann+Qzb=Mgt+San+Fay+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	775-790°C/1035 bars	Ann+Mgt=San+Wus+H_2O
Gustafson, 1974, J. Pet., 15, 455-496	G	401-529°C/2000 bars	Hed+Bun=Adr+Mgt+Qzb+Nic
Gustafson, 1974, J. Pet., 15, 455-496	G	748-797°C/500-2000 bars	Adr+Fay=Mgt+Wol+Qzb
Gustafson, 1974, J. Pet., 15, 455-496	G	789-839°C/500-2000 bars	Adr+Nil=Mgt+Wol+Nil
Hewitt, 1976, EOS, 57, 1020	G	650-850°C/1000 bars	Mgt+Qzb=Fay+Oxy
Komarov & others, 1967, Neorg. Mater., 3, 1064-1072	G(emf)	1273-1657 K/1 atm	Mgt+Oxy=Hem
Liou, 1973, J. Pet., 14, 381-413	G	630-762°C/2000-5000 bars	Ept+Mgt=(Gro+Adr+Alm)+Ano+Qza+Hem+H_2O
Rau, 1972, J. Chem. Thermodyn., 4, 57-64	G	859-882 K/1 atm	Mgt+H_2O=Wus+H_2O
Schmahl, 1941, Z. Electrochem., 47, 821-843	G	1583-1683 K/1 atm	Mgt+Oxy=Hem
Tret'yakov & Khomyakov, 1962, Russ. J. Inorg. Chem., 7, 628-631	G	1373-1728 K/1 atm	Mgt+Oxy=Hem
Vallet & Raccah, 1965, Mem. Sci. Rev. Metal., 62, 1-29	G	1133-1398 K/1 atm	Wus+CO_2=Mgt+CO
Wones & Gilbert, 1969, AJS, 267-A, 480-488	G	594-803°C/800-2000 bars	Mgt+Qzb=Fay+Oxy
Sharma, 1950, Proc. Indian Acad. Sci., A31, 261-274	V	314-843 K/1 atm	Mgt
Darken & Gurry, 1946, J. Am. Chem. Soc., 68, 798-816	a	1401-1866 K/1 atm	Mgt(FeO-Fe_2O_3 join)

Margarite $CaAl_4Si_2O_{10}(OH)_2$ - Mica group

Important solid solution

(CaAl,NaSi) Margarite - Paragonite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Perkins & others, 1980, Geochim. Cosmo. Acta, 44, 61-84	Cp	298-1000 K/1 atm	Mar
Perkins & others, 1980, Geochim. Cosmo. Acta, 44, 61-84	S	298.15 K/1 atm	Mar
Chatterjee, 1971, Naturw., 58, 147	G	763-893 K/1000-7000 bars	Ano+Cor+H_2O=Mar
Chatterjee, 1974, Schweiz. Min. Petrogr. Mitt., 54, 753-767	G	763-893 K/1000-7000 bars	Ano+Cor+H_2O=Mar
Nitsch, 1974, For. Min., 51, 34-35	G	325-445°C/4000-10000 bars	Law=Zoi+Mar+Qza+H_2O
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	763-833 K/4000-5000 bars	Ano+And+H_2O=Mar+Qzb
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	788-833 K/4000-5000 bars	Ano+And+H_2O=Mar+Qza
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	803-933 K/4000-5000 bars	Ano+Kya+H_2O=Mar+Qza
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Mar
Franz & others, 1977, Cont. Min. Pet., 59, 307-316	a	400-600°C/1000-6000 bars	Par+Mar($NaAl_3Si_3O_{10}(OH)_2$-$CaAl_4Si_2O_{10}(OH)_2$ join)
Franz & others, 1977, Cont. Min. Pet., 59, 307-316	dV/dX	25°C/1 atm	Par+Mar($NaAl_3Si_3O_{10}(OH)_2$-$CaAl_4Si_2O_{10}(OH)_2$ join)

Microcline $KAlSi_3O_8$ - Feldspar group

Al,Si ordered in tetrahedral sites

Important solid solution

(K,Na) Microcline - Albite, low join (alkali Feldspar series)

(AlSi order, AlSi disorder in tetrahedral sites) Microcline - Sanidine (K-Feldspar series)

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemingway & others, unpubl.	Cp	350-1000°C/1 atm	Mic
Openshaw & others, 1976, USGS J. Res., 4, 195-204	Cp	16-373 K/1 atm	Mic
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	400-1400 K/1 atm	Mic
Openshaw & others, 1976, USGS J. Res., 4, 195-204	S	298.15 K/1 atm	Mic
Waldbaum & Robie, 1971, Z. Krist., 184, 381-421	H	25°C/1 atm	Mic
Adams & Williamson, 1923, J. Franklin Inst., 195, 475-529	V	25°C/2000-12000 bars	Mic
Finney & Bailey, 1964, Z. Krist., 119, 413-436	V	25°C/1 atm	Mic
Hovis & Perkins, 1978, Cont. Min. Pet., 66, 345-349	V	25°C/1 atm	Mic
Openshaw & others, 1953, USGS J. Res., 4, 195-204	V	25°C/1 atm	Mic
Orville, 1967, Am. Min., 52, 55-86	dV/dX	25°C/1 atm	Mic+Alb($KAlSi_3O_8$-$NaAlSi_3O_8$ join)

Montmorillonite $(1/2Ca,Na)_{(x+y+z)}(Al_{2-x-2z},(Mg,Fe)_x,Fe_{+2}^{+3})(Al_{y+z},Si_{4-y-z})O_{10}(OH)_2 \cdot nH_2O$ - Nmt

Smectite Clay group, $x+y+z \leq 0.33$, $n \leq 2$

Generalized end-member components

Alkali-free Montmorillonite - $Al_2Si_4O_{10}(OH)_2 \cdot nH_2O$

Montmorillonite - $(1/2Ca,Na)_{0.33}(Al_{1.67},(Mg,Fe)_{0.33})Si_4O_{10}(OH)_2 \cdot nH_2O$

Beidellite - $(1/2Ca,Na)_{0.33}(Al_2)(Al_{0.33},Si_{3.67})O_{10}(OH)_2 \cdot nH_2O$

Nontronite - $(1/2Ca,Na)_{0.33}(Fe_2^{+3})(Al_{0.33},Si_{3.67})O_{10}(OH)_2 \cdot nH_2O$ - $n \leq 2$

* Composition of sample studied by phase equilibria experiments (G):

Na-Beidellite - $Na_{.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2$, $x = 0$, $y = 0.33$, $z = 0$, $n = 0$

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemley & others, 1961, USGS Prof. Paper 424-D, 338-340	G	330°C/1000 bars	Nmt+Alb=Qza+Par

Muscovite $KAl_3Si_3O_{10}(OH)_2$ - Mica group

Important solid solution

(K,Na) Muscovite - Paragonite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Krupka & others, 1979, Am. Min., 64, 86-101	Cp	333-967 K/1 atm	Mus
Robie & others, 1976, USGS J. Res., 4, 631-644	Cp	13-385 K/1 atm	Mus
Weller & King, 1963, US Bur. Mines Rpt. Inv. 6281, 4 p	Cp	53-297 K/1 atm	Mus
Melchakova & Topor, 1973, Moscow Univ. Geol. Bull., 28, 102-107	H_T-H_R	335-900 K/1 atm	Mus
Pankratz, 1964, US Bur. Mines Rpt. Inv. 6371, 6 p	H_T-H_R	394-903 K/1 atm	Mus
Robie & others, 1976, USGS J. Res., 4, 631-644	S	298.15 K/1 atm	Mus
Weller & King, 1963, US Bur. Mines Rpt. Inv. 6281, 4 p	S	298.15 K/1 atm	Mus
Barany, 1964, US Bur. Mines Rpt. Inv. 6356, 6 p	H	73.7°C/1 atm	Mus
Sommerfeld, 1967, J. Geol., 75, 477-487	H	80°C/1 atm	Mus
Bird & Fawcett, 1973, J. Pet., 14, 415-428	G	634-664°C/8270-9790 bars	$Cln+Mus=Phl+Kya+Qza+H_2O$
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	520-705°C/500-5000 bars	$Mus+Qza=San+And+H_2O$
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	540-720°C/500-6000 bars	$Mus+Qza=San+Sil+H_2O$
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	600-800°C/1000-8000 bars	$Mus=San+Cor+H_2O$
Day, 1973, Am. Min., 58, 255-262	G	580-668°C/1000-3000 bars	$Mus+Qza=San+Sil+H_2O$
Hewitt, D., 1973, Am. Min., 58, 785-791	G	448-610°C/2000-7000 bars	$Mus+Ccl+Qza=San+Ano+CO_2+H_2O$
Hewitt, D., 1973, Am. Min., 58, 785-791	G	539-540°C/6000 bars	$Mus+Ccl+Qza=San+Zoi+CO_2+H_2O$
Kerrick, 1972, AJS, 272, 946-958	G	600-610°C/2000 bars	$Mus+Qza=San+And+H_2O$
Yoder & Eugster, 1955, Geochim. Cosmo. Acta, 8, 255-277	V	25°C/1 atm	Mus
Blencoe, 1973, GSA Abs. Prog., 553-554	a	400-580°C/2000-8000 bars	Mus+Par ($KAl_3Si_3O_{10}(OH)_2-NaAl_3Si_3O_{10}(OH)_2$ join)
Eugster & others, 1972, J. Pet., 13, 147-179	a	300-600°C/2070 bars	Mus+Par ($KAl_3Si_3O_{10}(OH)_2-NaAl_3Si_3O_{10}(OH)_2$ join)
Eugster & others, 1972, J. Pet., 13, 147-179	dV/dX	25°C/1 atm	Mus+Par ($KAl_3Si_3O_{10}(OH)_2-NaAl_3Si_3O_{10}(OH)_2$ join)

Paragonite $NaAl_3Si_3O_{10}(OH)_2$ - Mica group

Important solid solution

(Na,K) Paragonite - Muscovite join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemingway & others, unpubl.	Cp	200-800 K/1 atm	Par
Hemingway & others, unpubl.	Cp	6-307 K/1 atm	Par
Hemingway & others, unpubl.	S	298.15 K/1 atm	Par
Chatterjee, 1970, Cont. Min. Pet., 27, 244-257	G	530-670°C/1000-7000 bars	Par=Ana+Cor+H_2O
Chatterjee, 1972, Cont. Min. Pet., 34, 288-303	G	470-600°C/1000-5000 bars	Par+Qza=Ana+And+H_2O
Chatterjee, 1972, Cont. Min. Pet., 34, 288-303	G	570-640°C/5000-7000 bars	Par+Qza=Ana+Kya+H_2O
Gusynin & Ivanov, 1971, Dokl. Akad. Nauk SSSR, 197, 1169-1170	G	490-510°C/1000 bars	Par+Qza=Ana+And+H_2O
Gusynin & Ivanov, 1971, Dokl. Akad. Nauk SSSR, 197, 1169-1170	G	530-550°C/1000 bars	Par=Ana+Cor+H_2O
Hemley & others, 1961, USGS Prof. Paper 424-D, 338-340	G	330°C/1000 bars	Nmt+Alb=Qza+Par
Holland, 1979, Cont. Min. Pet., 68, 293-301	G	550-700°C/23000-26000 bars	Par=Jad+Kya+H_2O
Chatterjee, 1974, Cont. Min. Pet., 43, 25-28	V	25°C/1 atm	Par
Holland, 1979, Cont. Min. Pet., 68, 293-301	V	25°C/1 atm	Par
Blencoe, 1973, GSA Abs. Prog., 553-554	a	400-580°C/2000-8000 bars	Mus+Par($KAl_3Si_3O_{10}(OH)_2$-$NaAl_3Si_3O_{10}(OH)_2$ join)
Eugster & others, 1972, J. Pet., 13, 147-179	a	300-600°C/2070 bars	Mus+Par($KAl_3Si_3O_{10}(OH)_2$-$NaAl_3Si_3O_{10}(OH)_2$ join)
Franz & others, 1977, Cont. Min. Pet., 59, 307-316	a	400-600°C/1000-6000 bars	Par+Mar($NaAl_3Si_3O_{10}(OH)_2$-$CaAl_4Si_2O_{10}(OH)_2$ join)
Eugster & others, 1972, J. Pet., 13, 147-179	dV/dX	25°C/1 atm	Mus+Par($KAl_3Si_3O_{10}(OH)_2$-$NaAl_3Si_3O_{10}(OH)_2$ join)
Franz & others, 1977, Cont. Min. Pet., 59, 307-316	dV/dX	25°C/1 atm	Par+Mar($NaAl_3Si_3O_{10}(OH)_2$-$CaAl_4Si_2O_{10}(OH)_2$ join)

Phlogophite $KMg_3AlSi_3O_{10}(OH)_2$ - Mica group, Biotite series

Important solid solution

(Mg,Fe) Phlogophite - Annite

$(MgSi,Al_2)$ Phlogophite - $KMg_2Al_3Si_2O_{10}(OH)_2$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Melchakova & Topor, 1973, Moscow Univ. Geol. Bull., 28, 102-107	H_T-H_R	335-1100 K/1 atm	Phl
Bird & Fawcett, 1973, J. Pet., 14, 415-428	G	634-664°C/8270-9790 bars	$Cln+Mus=Phl+Kya+Qza+H_2O$
Hewitt, D., 1975, Am. Min., 60, 391-397	G	460-681°C/2000-8000 bars	$Phl+Ccl+Qza=Tre+San+CO_2+H_2O$
Hoschek, 1973, Cont. Min. Pet., 39, 231-237	G	495-635°C/4000-6000 bars	$Phl+Ccl+Qza=Tre+San+CO_2+H_2O$
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	740-755°C/2000 bars	Tre+San=Phl+Dio+Qza
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	830-840°C/400-500 bars	$Phl+Qzb=San+Ens+H_2O$
Wones, 1967, Geochim. Cosmo. Acta, 31, 2248-2253	G	902-1018°C/100-400 bars	$Phl=Kal+Leu+For+H_2O$
Wood, 1976, Prog. Exp. Pet., Ser. D(6-1976), 17-19	G	750-790°C/300-470 bars	$Phl+Qzb=San+Ens+H_2O$
Adams & Williamson, 1923, J. Franklin Inst., 195, 475-529	V	25°C/1960-7840 bars	Phl
Hazen & Finger, 1978, Am. Min., 63, 293-296	V	25°C/1-47000 bars	Phl
Hewitt, 1975, Am. Min., 60, 391-397	V	25°C/1 atm	Phl
Takeda & Morosin, 1975, Acta Cryst., B31, 2444-2452	V	24-900°C/1 atm	Phl
Wones & Dodge, 1977, Thermo. in Geol., 229-247	V	25°C/1 atm	Phl
Wones, 1967, Geochim. Cosmo. Acta, 31, 2248-2253	V	25°C/1 atm	Phl

Prehnite $Ca_2Al_2Si_3O_{10}(OH)_2$

Reference	Data type	Range (Temperature/pressure)	Phases studied
Perkins & others, 1980, Geochim. Cosmo. Acta, 44, 61-84	Cp	200-298 K/1 atm	Pre
Perkins & others, 1980, Geochim. Cosmo. Acta, 44, 61-84	Cp	298-800 K/1 atm	Pre
Perkins & others, 1980, Geochim. Cosmo. Acta, 44, 61-84	S	298.15 K/1 atm	Pre
Liou, 1971, Am. Min., 56, 507-531	G	708-828 K/1974-5527 bars	Ano+Wol+H_2O=Pre
Liou, 1971, Am. Min., 56, 507-531	V	25°C/1 atm	Pre

Pyrite FeS_2 Pyt

Reference	Data type	Range (Temperature/pressure)	Phases studied
Gronvold & Westrum, 1962, Inorg. Chem., 1, 36-48	Cp	4.6-346 K/1 atm	Pyt
Gronvold & Westrum, 1976, J. Chem. Thermo., 8, 1039-1048	Cp	350-770 K/1 atm	Pyt
Coughlin, 1950, J. Am. Chem. Soc., 72, 5445-5448	H_T-H_R	298-980 K/1 atm	Pyt
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	400-1000 K/1 atm	Pyt
Gronvold & Westrum, 1962, Inorg. Chem., 1, 36-48	S	298.15 K/1 atm	Pyt
Kelley & King, 1961, US Bur. Mines Bull. 592, 149 p	S	298.15 K/1 atm	Pyt
Kullerup & Yoder, 1959, Econ. Geol., 54, 533-572	V	25°C/1 atm	Pyt
Arnold, 1962, Econ. Geol., 75, 72-90	a	325-736°C/1 atm	Pyo+Pyt($FeS-FeS_2$ join)
Toulmin & Barton, 1964, Geochim. Cosmo. Acta, 28, 641-671	a	305-490°C/1 atm	Pyo+Pyt($FeS-FeS_2$ join)
Toulmin & Barton, 1964, Geochim. Cosmo. Acta, 28, 641-671	a	305-654°C/1 atm	Pyo+Pyt($FeS-FeS_2$ join)

Pyrope — $Mg_3Al_2Si_3O_{12}$ - Garnet group

Important solid solution

(Mg,Fe)	Pyrope - Almandine join
(Mg,Ca)	Pyrope - Grossular join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Haselton & Westrum, 1980, Geochim. Cosmo. Acta, 44, 701-709	Cp	8-345 K/1 atm	Pyp
Kolesnik & others, 1977, Geokhim., 533-541	Cp		Pyp
Thompson & others, 1977, EOS, 58, 523	Cp	350-1000 K/1 atm	Pyp
Kisleva & others, 1972, Geochem. Int., 9, 1087	H_T-H_R	298-1100 K/1 atm	Pyp
Haselton & Westrum, 1980, Geochim. Cosmo. Acta, 44, 701-709	S	298.15 K/1 atm	Pyp
Kolesnik & others, 1977, Geokhim., 533-541	S	298.15 K/1 atm	Pyp
Charlu & others, 1975, Geochim. Cosmo. Acta, 39, 1487-1497	H	970 K/1 atm	Pyp=Per+Cor+Qzb
Hensen & Essene, 1971, Cont. Min. Pet., 30, 72-83	G	1000-1400°C/14400-19800 bars	Ens+Sil=Pyp+Qza
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	870-900°C/22000-35000 bars	Cln=Pyp+For+Spl+H_2O
Staudigel & Schreyer, 1977, Cont. Min. Pet., 61, 187-198	G	900-970°C/20000-21000 bars	Pyp+For=Ens+Spl
Hazen & Finger, 1978, Am. Min., 63, 297-303	V	25°C/1-56000 bars	Pyp
Levien & others, 1979, Am. Min., 64, 805-808	V	24°C/1-49600 bars	Pyp
Lieberman & Gondall, 1952, J. Am. Ceram. Soc., 35, 304-308	V	293-343 K/1 atm	Pyp
Meagher, 1975, Am. Min., 60, 218-228	V	25°C/1 atm	Pyp
Sato & others, 1978, JGR, 83, 335-338	V	25°C/8200-100900 bars	Pyp
Newton & others, 1977, Geochim. Cosmo. Acta, 41, 369-377	dH/dX	970 K/1 atm	Gro+Pyp($Ca_3Al_2Si_3O_{12}$-$Mg_3Al_2Si_3O_{12}$ join)
Newton & others, 1977, Geochim. Cosmo. Acta, 41, 369-377	dV/dX	25°C/1 atm	Gro+Pyp($Ca_3Al_2Si_3O_{12}$-$Mg_3Al_2Si_3O_{12}$ join)

Pyrophyllite $Al_2Si_4O_{10}(OH)_2$

Reference	Data type	Range (Temperature/pressure)	Phases studied
Krupka & others, 1979, Am. Min., 64, 86-101	Cp	335-680 K/1 atm	Pyr
Robie & others, 1976, USGS J. Res., 4, 631-644	Cp	200-370 K/1 atm	Pyr
Haas & Holdaway, 1973, AJS, 273, 449-464	G	618-722 K/2400-7000 bars	Pyr+Dia=And+H_2O
Haas & Holdaway, 1973, AJS, 273, 449-464	G	643-737 K/2400-7000 bars	And+Qza+H_2O=Pyr
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Kao+Qza=Pyr+H_2O
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	523-598 K/1000 bars	Dia+Qza=Pyr
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	613-673 K/1000 bars	And+Qza+H_2O=Pyr
Kerrick, 1968, AJS, 266, 204-214	G	668-718 K/1800-3900 bars	And+Qza+H_2O=Pyr
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	310-390°C/4000-7000 bars	Ccl+Pyr+H_2O=Law+Qza+CO_2
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	340-385°C/4000-5000 bars	Law=Zoi+Kya+Pyr+H_2O
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	370-430°C/7000 bars	Law+Qza=Zoi+Pyr+H_2O
Krupka & others, 1979, Am. Min., 64, 86-101	V	25°C/1 atm	Pyr
Taylor & Bell, 1970, Carn. Inst. Wash. Yb., 193-194	V	22-402°C/1 atm	Pyr

Pyrrhotite $Fe_{1-x}S$, x = 0-0.125 Pyo

Reference	Data type	Range (Temperature/pressure)	Phases studied
Gronvold & others, 1959, J. Chem. Phys., 30, 528-531	Cp	5-350 K/1 atm	Pyo
Coughlin, 1950, J. Am. Chem. Soc., 72, 5445-5448	H_T-H_R	298-1488 K/1 atm	Pyo
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	350-2000 K/1 atm	Pyo
Gronvold & others, 1959, J. Chem. Phys., 30, 528-531	S	298.15 K/1 atm	Pyo
Kelley & King, 1961, US Bur. Mines Bull. 592, 149 p	S	298.15 K/1 atm	Pyo
Adams & King, 1964, US Bur. Mines Rpt. Inv. 6495, 10 p	H	73.7°C/1 atm	Pyo
Fizeau, 1888, Ann. pour l'an Paris, Bur. longitudes	$\dot{V}$	293-343 K/1 atm	Pyo
Arnold, 1962, Econ. Geol., 75, 72-90	a	325-736°C/1 atm	Pyo+Pyt($FeS-FeS_2$ join)
Toulmin & Barton, 1964, Geochim. Cosmo. Acta, 28, 641-671	a	305-490°C/1 atm	Pyo+Pyt($FeS-FeS_2$ join)
Toulmin & Barton, 1964, Geochim. Cosmo. Acta, 28, 641-671	a	305-654°C/1 atm	Pyo+Pyt($FeS-FeS_2$ join)
Toulmin & Barton, 1964, Geochim. Cosmo. Acta, 28, 641-671	a	389-909°C/1 atm	Pyo($FeS-FeS_2$ join)
Haraldsen, 1941, Z. Anorg. Chem., 246, 169-194	dV/dX	25°C/1 atm	Pyo($FeS-FeS_2$ join)
Toulmin & Barton, 1964, Geochim. Cosmo. Acta, 28, 641-671	dV/dX	25°C/1 atm	Pyo($FeS-FeS_2$ join)

Quartz - alpha, beta SiO_2 - polymorph with Tridymite, Cristobalite, Coesite, Stishovite Qza,Qzb

Reference	Data type	Range (Temperature/pressure)	Phases studied
Chase & others, 1974, J. Phys. Chem. Ref. Data, 3, 311-480	Cp		Qza
Chase & others, 1975, J. Phys. Chem. Ref. Data, 4, 1-176	Cp		Qza
Stull & Prophet, 1971, US NBS NSRDS-NBS 37	Cp		Qza
CODATA Task Group, 1978, CODATA Bull., 28, 1-16	S		Qza
Anderson & Kleppa, 1969, AJS, 267, 285-290	H	974 K/1 atm	Kya=Cor+Qza
Anderson & others, 1977, AJS, 277, 585-593	H	973 K/1 atm	Cor+Qza=And
Barany & Kelley, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	H	346.85 K/1 atm	Hal+H_2O=Qza+Glb
Barany & Kelley, 1961, US Bur. Mines Rpt. Inv. 5810, 6 p	H	346.85 K/1 atm	Kao+H_2O=Qza+Glb
Barany & Kelley, 1961, US Bur. Mines Rpt. Inv. 5825, 13 p	H	346.85 K/1 atm	Dic+H_2O=Qza+Hib
Barany, 1963, US Bur. Mines Rpt. Inv. 6251, 9 p	H	25°C/1 atm	Tlc=Per+Qza+H_2O
Barany, 1966, US Bur. Mines Rpt. Inv. 6784, 8 p	H	346.85 K/1 atm	Wol=Qza+Lme
CODATA Task Group, 1978, CODATA Bull., 28, 1-16	H		Qza
Charlu & others, 1975, Geochim. Cosmo. Acta, 39, 1487-1497	H	970 K/1 atm	Ens=Per+Qzb
Charlu & others, 1975, Geochim. Cosmo. Acta, 39, 1487-1497	H	970 K/1 atm	Pyp=Per+Cor+Qzb
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Ano=Lme+Cor+Qza
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Cts=Lme+Cor+Qza
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Gro=Lme+Cor+Qzb
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Lme+Qzb=Cwo
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Sil=Cor+Qzb
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Wol=Qzb+Lme
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Dio=Lme+Per+Qzb
King & others, 1967, US Bur. Mines Rpt. Inv. 6962, 19 p	H	25°C/1 atm	For=Per+Qza
King, 1951, J. Am. Chem. Soc., 73, 656-658	H	346.85 K/1 atm	Lar=Qza+Lme
Kracek & Neuvonen, 1952, AJS, Bowen Vol., 293-318	H	347.85 K/1 atm	Ano+H_2O=Lme+Glb+Qza

Kracek & others, 1953, Carn. Inst. Wash. Yb., 69-74	H	74.7°C/1 atm	Dio=Lme+Per+Qza
Navrotsky & Coons, 1976, Geochim. Cosmo. Acta, 40, 1281-1288	H	970 K/1 atm	Dio=Lme+Per+Qzb
Shearer & Kleppa, 1973, J. Inorg. Nuc. Chem., 35, 1073-1078	H	965-1173 K/1 atm	Ens=Per+Qzb
Shearer & Kleppa, 1973, J. Inorg. Nuc. Chem., 35, 1073-1078	H	965-1173 K/1 atm	For+Per+Qzb
Weeks, 1956, J. Geol., 64, 456-472	H	81°C/1 atm	Tre=Ran+Ant+Qza+H_2O
Benz & Wagner, 1961, J. Phys. Chem., 65, 1308-1311	G(emf)	898-1148 K/1 atm	Wol=Qzb+Lme
Birch & LeComte, 1960, AJS, 258, 209-217	G	802-1007°C/21280-26040 bars	Ana=Jad+Qza
Bird & Fawcett, 1973, J. Pet., 14, 415-428	G	634-664°C/8270-9790 bars	Cln+Mus=Phl+Kya+Qza+H_2O
Boettcher, 1970, J. Pet., 11, 337-379	G	853-933 K/4000-5300 bars	Gro+Ano+H_2O=Zoi+Qza
Boettcher, 1970, J. Pet., 11, 337-379	G	893-1053 K/3000-5900 bars	Ano+Wol=Gro+Qzb
Bohlen & others, 1980, Earth Planet. Sci. Lett., 47, 1-10	G	700-850°C/10500-12000 bars	Fes=Fay+Qza
Bohlen & others, 1980, Earth Planet. Sci. Lett., 47, 1-10	G	900-1050°C/12500-15000 bars	Fes=Fay+Qzb
Boyd, 1959, Res. Geochem., 1, 377-395	G	800-880°C/575-2000 bars	Tre=Dio+Ens+Qza+H_2O
Campbell & Fyfe, 1965, AJS, 263, 807-816	G	175-210°C/8.9-19 bars	Anl+Qza=Alb+H_2O
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	520-705°C/500-5000 bars	Mus+Qza=San+And+H_2O
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	540-720°C/500-6000 bars	Mus+Qza=San+Sil+H_2O
Chatterjee, 1972, Cont. Min. Pet., 34, 288-303	G	470-600°C/1000-5000 bars	Par+Qza=Ana+And+H_2O
Chatterjee, 1972, Cont. Min. Pet., 34, 288-303	G	570-640°C/5000-7000 bars	Par+Qza=Ana+Kya+H_2O
Chernosky & Autio, 1979, Am. Min., 64, 294-303	G	647-742°C/500-3000 bars	Tlc=Ant+Qzb+H_2O
Chernosky & Autio, 1979, Am. Min., 64, 294-303	G	664-775°C/500-2000 bars	Ant=Ens+Qzb+H_2O
Chernosky, 1976, Am. Min., 61, 1145-1155	G	648-744°C/500-2000 bars	Tlc=Ens+Qza+H_2O
Chernosky, 1978, Am. Min., 63, 73-82	G	504-581°C/2000-4000 bars	Cln+Qza=Tlc+Crd+H_2O
Chou, 1978, Am. Min., 63, 690-703	G	600-800°C/2000-4000 bars	Mgt+Qzb=Fay+Oxy
Day, 1971, PhD Thesis, Brown Univ.	G		Fec+San+H_2O=Ann+Sil+Qza
Day, 1973, Am. Min., 58, 255-262	G	580-668°C/1000-3000 bars	Mus+Qza=San+Sil+H_2O
Essene & others, 1972, EOS, 53, 544	G	800-1200°C/20500-31000 bars	Ana=Jad+Qza
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	540-550°C/1035 bars	Ann+Qzb+Irn=San+Fay+Wus+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	650-710°C/1035-2070 bars	Ann+Qzb=Mag+San+Fay+H_{20}

Goldsmith, 1980, Am. Min., 65, 272-284	G	1100-1400°C/22000-31000 bars	Ano=Gro+Kya+Qza
Gordon & Greenwood, 1970, AJS, 268, 225-242	G	410-522°C/2000 bars	Dol+Qza=Mcc+Tlc+CO_2
Gordon & Greenwood, 1970, AJS, 268, 225-242	G	450-519°C/2000 bars	Dol+Qza=Mcc+Tlc+CO_2
Greenwood, 1963, J. Pet., 4, 317-351	G	694-711°C/2000 bars	Tlc=Ant+Qzb+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	703-775°C/2000-2600 bars	Tlc=Ens+Qzb+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	750-775°C/2000-2600 bars	Ant=Ens+Qzb+H_2O
Greenwood, 1967, Am. Min., 52, 1669-1680	G	558-595°C/1000-2000 bars	Ccl+Qza=Wol+CO_2
Greenwood, 1967, Am. Min., 52, 1669-1680	G	609-723°C/1000-2000 bars	Ccl+Qzb=Wol+CO_2
Gustafson, 1974, J. Pet., 15, 455-496	G	401-529°C/2000 bars	Hed+Bun=Adr+Mag+Qzb+Nic
Gustafson, 1974, J. Pet., 15, 455-496	G	748-797°C/500-2000 bars	Adr+Fay=Mag+Wol+Qzb
Gusynin & Ivanov, 1971, Ookl. Akad. Nauk SSSR, 197, 1169-1170	G	490-510°C/1000 bars	Par+Qza=Ana+And+H_2O
Haas & Holdaway, 1973, AJS, 273, 449-464	G	643-737 K/2400-7000 bars	And+Qza+H_2O=Pyr
Harker & Tuttle, 1956, AJS, 254, 239-256	G	600-800°C/300-2400 bars	Ccl+Qzb=Wol+CO_2
Haselton & others, 1978, Geophys. Res. Lett., 5, 753-756	G	1000-1325°C/10000-19000 bars	Cc2+Qzb=Wol+CO_2
Hemley & others, 1961, USGS Prof. Paper 424-D, 338-340	G	330°C/1000 bars	Nmt+Alb=Qza+Par
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Boe+Qza+H_2O=Kao
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Dia+Qza+H_2O=Kao
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	473-573 K/1000 bars	Kao+Qza=Pyr+H_2O
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	523-598 K/1000 bars	Dia+Qza=Pyr
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	623-663 K/1000 bars	Dia+Qza=And+H_2O
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	723-773 K/1000 bars	Cor+Qza=And
Hemley & others, 1980, Econ. Geol., 75, 210-228	G	613-673 K/1000 bars	And+Qza+H_2O=Pyr
Hensen & Essene, 1971, Cont. Min. Pet., 30, 72-83	G	1000-1400°C/14400-19800 bars	Ens+Sil=Pyp+Qza
Hewitt, 1976, EOS, 57, 1020	G	650-850°C/1000 bars	Mgt+Qzb=Fay+Oxy
Hewitt, D., 1973, Am. Min., 58, 785-791	G	448-610°C/2000-7000 bars	Mus+Ccl+Qza=San+Ano+CO_2+H_2O
Hewitt, D., 1973, Am. Min., 58, 785-791	G	539-540°C/6000 bars	Mus+Ccl+Qza=San+Zoi+CO_2+H_2O
Holdaway & Lee, 1977, Cont. Min. Pet., 63, 175-198	G	624-775°C/2700-3800 bars	Fec=Alm+Sil+Qza+H_2O
Holdaway & Lee, 1977, Cont. Min. Pet., 63, 175-198	G	641-710°C/1900-2800 bars	Fec+San+H_2O=Ann+Sil+Qza

Holdaway & Lee, 1977, Cont. Min. Pet., 63, 175-198	G	774-776°C/2700-2900 bars	Fec=Hcy+Qza+H_2O
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	848-858 K/1000-3000 bars	Ano+Wol=Gro+Qza
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	888-958 K/4000 bars	Ano+Wol=Gro+Qzb
Johannes & others, 1971, Cont. Min. Pet., 32, 24-38	G	600°C/15700-16800 bars	Ana=Jad+Qza
Johannes, 1969, AJS, 267, 1083-1104	G	300-600°C/330-7000 bars	Tlc+CO_2=Qza+Mag+H_2O
Juan & Lo, 1971, Proc. Geol. Soc. China, 14, 34-44	G	292-469°C/690-1380 bars	Wal=Ano+Qza+H_2O
Kerrick, 1968, AJS, 266, 204-214	G	668-718 K/1800-3900 bars	And+Qza+H_2O=Pyr
Kerrick, 1972, AJS, 272, 946-958	G	600-610°C/2000 bars	Mus+Qza=San+And+H_2O
Lindsley, 1965, Carn. Inst. Wash. Yb., 148-150	G	1000-1100°C/15500-17000 bars	Fes=Fay+Qza
Lindsley, 1965, Carn. Inst. Wash. Yb., 148-150	G	1275-1280°C/1700-1750 bars	Pfs=Fay+Qza
Liou, 1970, Cont. Min. Pet., 27, 259-282	G	325-393°C/500-5000 bars	Wal=Ano+Qza+H_2O
Liou, 1971, Cont. Min. Pet., 31, 171-177	G	175-200°C/3000-5000 bars	Stl=Lau+Qza+H_2O
Liou, 1971, J. Pet., 12, 379-411	G	194-249°C/2800-3500 bars	Lau=Law+Qza+H_2O
Liou, 1971, J. Pet., 12, 379-411	G	297-381°C/3200-4350 bars	Wal=Law+Qza
Liou, 1971, Lithos, 4, 389-402	G	178-210°C/2000-5000 bars	Ana+Qza=Alb+H_2O
Liou, 1973, J. Pet., 14, 381-413	G	630-762°C/2000-5000 bars	Ept+Mgt=(Gro+Adr+Alm)+Ano+Qza+Hem+H_2O
Liou, 1974, Am. Min., 59, 1016-1025	G	570-610°C/500-2000 bars	Adr+Qza+Fay=Hed+Wol
Liou, 1974, Am. Min., 59, 1016-1025	G	621-683°C/500-2000 bars	Adr+Qza+Nic=Hed+Wol+Bun
Lo, 1978, Proc. Geol. Soc. China, 21, 25-33	G	258-308°C/690-2069 bars	Epl=Wal+Qza+H_2O
Metz & Winkler, 1963, Geochim. Cosmo. Acta, 27, 431-457	G	440-510°C/2000 bars	Dol+Qza=Mcc+Tlc+CO_2
Newton & Smith, 1967, J. Geol., 75, 268-286	G	500-600°C/13500-16900 bars	Ana=Jad+Qza
Newton, 1966, AJS, 264, 204-222	G	803-923 K/1100-2000 bars	Ano+Wol=Gro+Qza
Newton, 1966, AJS, 264, 204-222	G	973-1023 K/4700-5700 bars	Ano+Wol=Gro+Qzb
Nitsch, 1968, Naturw., 55, 388	G	160-210°C/7000 bars	Heu=Law+Qza+H_2O
Nitsch, 1968, Naturw., 55, 388	G	345°C/2500-3500 bars	Lau=Law+Qza+H_2O
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	310-390°C/4000-7000 bars	Ccl+Pyr+H_2O=Law+Qza+CO_2
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	370-430°C/7000 bars	Law+Qza=Zoi+Pyr+H_2O
Nitsch, 1974, For. Min., 51, 34-35	G	325-445°C/4000-10000 bars	Law=Zoi+Mar+Qza+H_2O

Richardson, 1968, J. Pet., 9, 467-488	G		Fec=Alm+Sil+Qza+H_2O
Richardson, 1968, J. Pet., 9, 467-488	G		Fec=Hcy+Qza+H_2O
Smith, 1971, AJS, 271, 370-382	G	1075-1100°C/15500-18000 bars	Fes=Fay+Qzb
Smith, 1971, AJS, 271, 370-382	G	750-900°C/11000-15000 bars	Fes=Fay+Qza
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	763-833 K/4000-5000 bars	Ano+And+H_2O=Mar+Qzb
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	788-833 K/4000-5000 bars	Ano+And+H_2O=Mar+Qza
Storre & Nitsch, 1974, Cont. Min. Pet., 43, 1-24	G	803-933 K/4000-5000 bars	Ano+Kya+H_2O=Mar+Qza
Strens, 1968, Min. Mag., 36, 864-867	G	770-823 K/2000 bars	Gro+Ano+H_2O=Zoi+Qza
Taylor & Liou, 1978, Am. Min., 63, 378-393	G	498-600°C/2000 bars	Qza+Ccl+Hem=Adr+CO_2
Thompson, 1970, AJS, 269, 267-275	G	250°C/2500-3000 bars	Lau=Law+Qza+H_2O
Thompson, 1970, AJS, 269, 267-275	G	300-357°C/1000-6000 bars	Lau=Ano+Qza+H_2O
Thompson, 1971, AJS, 271, 79-92	G	150-200°C/2000-5500 bars	Anl+Qza=Alb+H_2O
Thompson, 1976, Prog. Exp. Pet., Ser. D(6-1976), 12-13	G	390-465°C/500-2000 bars	Ccl+And+Qza=Ano+CO_2
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	726-774°C/400 bars	Tre=Dio+Ens+Qza+H_2O
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	740-755°C/2000 bars	Tre+San=Phl+Dio+Qza
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	830-840°C/400-500 bars	Phl+Qzb=San+Ens+H_2O
Wones & Gilbert, 1969, AJS, 267-A, 480-488	G	594-803°C/800-2000 bars	Mgt+Qzb=Fay+Oxy
Wood, 1976, Prog. Exp. Pet., Ser. D(6-1976), 17-19	G	750-790°C/300-470 bars	Phl+Qzb=San+Ens+H_2O
Yoder, 1950, EOS, 31, 827-835	G	572-815°C/1-10000 bars	Qza=Qzb
Adams & others, 1919, J. Am. Chem. Soc., 41, 12-42	V	25°C/1960-12000 bars	Qza
Jay, 1933, Proc. Roy. Soc. Lond., Ser. A, 142, 237-247	V	18-579°C/1 atm	Qza
Jay, 1933, Proc, Roy. Soc. Lond., Ser. A, 142, 237-247	V	590-730°C/1 atm	Qzb
Olinger & Halleck, 1976, JGR, 81, 5711-5714	V	25°C/33800-120700 bars	Qza
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Qza
Vaidya & others, 1973, JGR, 78, 6893-6898	V	25°C/5000-45000 bars	Qza

Sanidine KAlSi$_3$O$_8$ - Feldspar group

Al,Si disordered in tetrahedral sites

Important solid solution

(K,Na)	Sanidine - Analbite join (alkali Feldspar series)
(AlSi disorder, AlSi order in tetrahedral sites)	Sanidine - Microcline join (K-Feldspar series)

Reference	Data type	Range (Temperature/pressure)	Phases studied
Hemingway & others, unpubl.	Cp	340-978 K/1 atm	San
Openshaw & others, 1976, USGS J. Res., 4, 195-204	Cp	16-376 K/1 atm	San
Kelley, 1960, US Bur. Mines Bull. 584, 232 p	H_T-H_R	400-1400 K/1 atm	San
Openshaw & others, 1976, USGS J. Res., 4, 195-204	S	298.15 K/1 atm	San
Hemingway & others, unpubl.	H	49.7°C/1 atm	San
Hovis, 1972, Proc. NATO Adv. Study Inst., 114-144	H	49.7°C/1 atm	San
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	520-705°C/500-5000 bars	Mus+Qza=San+And+H_2O
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	540-720°C/500-6000 bars	Mus+Qza=San+Sil+H_2O
Chatterjee & Johannes, 1974, Cont. Min. Pet., 48, 89-114	G	600-800°C/1000-8000 bars	Mus=San+Cor+H_2O
Day, 1971, PhD Thesis, Brown Univ.	G		Fec+San+H_2O=Ann+Sil+Qza
Day, 1973, Am. Min., 58, 255-262	G	580-668°C/1000-3000 bars	Mus+Qza=San+Sil+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	540-550°C/1035 bars	Ann+Qzb+Irn=San+Fay+Wus+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	610-640°C/1035-2070 bars	Ann+Bun=San+Mag+Nil+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	650-710°C/1035-2070 bars	Ann+Qzb=Mag+San+Fay+H_2O
Eugster & Wones, 1962, J. Pet., 3, 82-125	G	775-790°C/1035 bars	Ann+Mag=San+Wus+H_2O
Hewitt, D., 1973, Am. Min., 58, 785-791	G	448-610°C/2000-7000 bars	Mus+Ccl+Qza=San+Ano+CO_2+H_2O
Hewitt, D., 1973, Am. Min., 58, 785-791	G	539-540°C/6000 bars	Mus+Ccl+Qza=San+Zoi+CO_2+H_2O
Hewitt, D., 1975, Am. Min., 60, 391-397	G	460-681°C/2000-8000 bars	Phl+Ccl+Qza=Tre+San+CO_2+H_2O

Holdaway & Lee, 1977, Cont. Min. Pet., 63, 175-198	G	641-710°C/1900-2800 bars	Fec+San+H_2O=Ann+Sil+Qza
Hoschek, 1973, Cont. Min. Pet., 39, 231-237	G	495-635°C/4000-6000 bars	Phl+Ccl+Qza=Tre+San+CO_2+H_2O
Kerrick, 1972, AJS, 272, 946-958	G	600-610°C/2000 bars	Mus+Qza=San+And+H_2O
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	740-755°C/2000 bars	Tre+San=Phl+Dio+Qza
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	830-840°C/400-500 bars	Phl+Qzb=San+Ens+H_2O
Wood, 1976, Prog. Exp. Pet., Ser. D(6-1976), 17-19	G	750-790°C/300-470 bars	Phl+Qzb=San+Ens+H_2O
Hovis, 1972, Proc. NATO Adv. Study Inst., 114-144	V	25°C/1 atm	San
Openshaw & others, 1976, USGS J. Res., 4, 195-204	V	25°C/1 atm	San
Wones & Oodge, 1977, Thermo. in Geol., 229-247	V	25°C/1 atm	San
Hovis & Waldbaum, 1977, Am. Min., 62, 680-686	dH/dX	49.7°C/1 atm	San+Ana($KAlSi_3O_8$-$NaAlSi_3O_8$ join)
Waldbaum & Robie, 1971, Z. Krist., 134, 381-420	dH/dX	49.7°C/1 atm	San+Ana($KAlSi_3O_8$-$NaAlSi_3O_8$ join)
Hovis, 1977, Am. Min., 62, 672-679	dV/dX	25°C/1 atm	San+Ana($KAlSi_3O_8$-$NaAlSi_3O_8$ join)
Orville, 1967, Am. Min., 52, 55-86	dV/dX	25°C/1 atm	San+Ana($KAlSi_3O_8$-$NaAlSi_3O_8$ join)

Reference	Data type	Range (Temperature/pressure)	Phases studied
Chase & others, 1974, J. Phys. Chem. Ref. Data, 3, 311-480	Cp		H_2O
Chase & others, 1975, J. Phys. Chem. Ref. Data, 4, 1-176	Cp		H_2O
Stull & Prophet, 1971, US NBS NSRDS-NBS 37	Cp		H_2O
Wolley, 1980, Cont. 9th Int. Conf. Prop. Steam, Munich	Cp	50-4000 K/1 atm	H_2O
Haar & others, 1980, Cont. 9th Int. Conf. Prop. Steam, Munich	S	0-900°C/0-10000 bars	H_2O
CODATA Task Group, 1978, CODATA Bull., 28, 1-16	S		H_2O
Wolley, 1980, Cont. 9th Int. Conf. Prop. Steam, Munich	S	50-4000 K/1 atm	H_2O
CODATA Task Group, 1978, CODATA Bull., 28, 1-16	H		H_2O
Haar & others, 1980, Cont. 9th Int. Conf. Prop. Steam, Munich	H	0-900°C/0-10000 bars	H_2O
Wolley, 1980, Cont. 9th Int. Conf. Prop. Steam, Munich	H	50-4000 K/1 atm	H_2O
Haar & others, 1980, Cont. 9th Int. Conf. Prop. Steam, Munich	G	0-900°C/0-10000 bars	H_2O
Greenwood & Barnes. 1966, GSA Mem., 97, 385-400	P-V-T	12-750°C/25-2000 bars	$CO_2+H_2O(CO_2-H_2O$ join)
Greenwood, 1969, AJS, 267-A, 191-208	P-V-T	450-800°C/1-500 bars	$CO_2+H_2O(CO_2-H_2O$ join)
Haar & others, 1980, Cont. 9th Int. Conf. Prop. Steam, Munich	P-V-T	0-900°C/0-10000 bars	H_2O
Liley, 1956, Rpt. Brit. Admir. DEMR/EN/32/16/1/56	P-V-T		$CO_2+H_2O(CO_2-H_2O$ join)
Powell & others, 1979, Prog. Astronau. Aeronau., 66, 325-348	P-V-T	0-900°C/0-10000 bars	$CO_2+H_2O(CO_2-H_2O$ join)
Takenouchi & Kennedy, 1964, AJS, 262, 1055-1074	P-V-T	110-350°C/1-1600 bars	$CO_2+H_2O(CO_2-H_2O$ join)

Stilbite $CaAl_2Si_7O_{18}\cdot 7H_2O$ - Zeolite group

Important solid solution

(Ca,Na_2)	Stilbite - $Na_2Al_2Si_7O_{18}\cdot 7H_2O$ join
$(CaAl,NaSi)$	Stilbite - $NaAlSi_8O_{18}\cdot 7H_2O$ join
$(H_2O,[])$	Stilbite - $CaAl_2Si_7O_{18}\cdot 7[]$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Liou, 1971, Cont. Min. Pet., 31, 171-177	G	175-200°C/3000-5000 bars	$Stl = Lau + Qza + H_2O$
Liou, 1971, Cont. Min. Pet., 31, 171-177	V	25°C/1 atm	Stl

Talc $Mg_3Si_4O_{10}(OH)_2$ Tlc

Reference	Data type	Range (Temperature/pressure)	Phases studied
Krupka & others, 1977, GSA Abs. Prog., 9, 1060; Krupka, unpubl.	Cp	350-800 K/1 atm	Tlc
Robie & Stout, 1963, J. Phys. Chem., 67, 2252-2256	S	298.15 K/1 atm	Tlc
Barany, 1963, US Bur. Mines Rpt. Inv. 6251, 9 p	H	25°C/1 atm	Tlc=Per+Qza+H_2O
Chernosky & Autio, 1979, Am. Min., 64, 294-303	G	647-742°C/500-3000 bars	Tlc=Ant+Qzb+H_2O
Chernosky, 1976, Am. Min., 61, 1145-1155	G	600-706°C/500-4000 bars	Tlc+For=Ens+H_2O
Chernosky, 1976, Am. Min., 61, 1145-1155	G	648-744°C/500-2000 bars	Tlc=Ens+Qza+H_2O
Chernosky, 1978, Am. Min., 63, 73-82	G	504-581°C/2000-4000 bars	Cln+Qza=Tlc+Crd+H_2O
Evans & others, 1976, Schweig. Min. Pet. Mitt., 56, 79-93	G	480-660°C/2000-15000 bars	Atg=For+Tlc+H_2O
Gordon & Greenwood, 1970, AJS, 268, 225-242	G	410-522°C/2000 bars	Dol+Qza=Mcc+Tlc+CO_2
Gordon & Greenwood, 1970, AJS, 268, 225-242	G	450-519°C/2000 bars	Dol+Qza=Mcc+Tlc+CO_2
Greenwood, 1963, J. Pet., 4, 317-351	G	662-712°C/2000-2600 bars	Tlc+For=Ens+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	663-679°C/1000-4000 bars	For+Tlc=Ant+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	694-711°C/2000 bars	Tlc=Ant+Qzb+H_2O
Greenwood, 1963, J. Pet., 4, 317-351	G	703-775°C/2000-2600 bars	Tlc=Ens+Qzb+H_2O
Hemley & others, 1977, AJS, 277, 322-351	G	450-600°C/1000 bars	For+Hsi=Tlc+H_2O
Hemley & others, 1977, AJS, 277, 322-351	G	90-450°C/1 atm-2000 bars	Chr+Hsi=Tlc+H_2O†
Hemley & others, 1977, AJS, 277, 353-383	G	300-450°C/1000 bars	Atg+Hsi=Tlc+H_2O
Hemley & others, 1977, AJS, 277, 353-383	G	550-640°C/1000 bars	For+Hsi=Tlc+H_2O
Hemley & others, 1977, AJS, 277, 353-383	G	640-670°C/1000 bars	Ant+Hsi=Tlc+H_2O
Hemley & others, 1977, AJS, 277, 353-383	G	649-690°C/1000 bars	Ens+Hsi=Tlc+H_2O
Johannes, 1969, AJS, 267, 1083-1104	G	300-600°C/330-7000 bars	Tlc+CO_2=Qza+Mag+H_2O
Johannes, 1969, AJS, 267, 1083-1104	G	340-490°C/1000-4000 bars	Chr+CO_2=Tlc+Mag+H_2O
Johannes, 1969, AJS, 267, 1083-1104	G	450-660°C/500-7000 bars	For+H_2O+CO_2=Tlc+Mag

Metz & Winkler, 1963, Geochim. Cosmo. Acta, 27, 431-457	G	440-510°C/2000 bars	$Dol+Qza=Mcc+Tlc+CO_2$
Chernosky & Autio, 1979, Am. Min., 64, 294-303	V	25°C/1 atm	Tlc
Hemley & others, 1977, AJS, 277, 322-315	V	25°C/1 atm	Tlc
Koishi & Gillies, 1979, Am. Min., 64, 211-214	V	25-600°C/1 atm	Tlc
Stemple & Brindley, 1960, J. Am. Ceram. Soc., 43, 34-42	V	25°C/1 atm	Tlc
Vaidya & others, 1973, JGR, 78, 6893-6898	V	25°C/5000-45000 bars	Tlc

Tremolite

$Ca_2Mg_5Si_8O_{22}(OH)_2$ - Amphibole group

Important solid solution

(Mg,Fe)	Tremolite - $Ca_2Fe_5Si_8O_{22}(OH)_2$ join
(MgSi,Al$_2$)	Tremolite - $Ca_2Mg_3Al_4Si_6O_{22}(OH)_2$ join
(Si,NaAl)	Tremolite - $NaCa_2Mg_5AlSi_7O_{22}(OH)_2$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Krupka & others, 1977, GSA Abs. Prog., 9, 1060; Krupka, unpubl.	Cp	350-800 K/1 atm	Tre
Robie & Stout, 1963, J. Phys. Chem., 67, 2252-2256	Cp	12-305 K/1 atm	Tre
Robie & Stout, 1963, J. Phys. Chem., 67, 2252-2256	S	298.15 K/1 atm	Tre
Weeks, 1956, J. Geol., 64, 456-472	H	81°C/1 atm	Tre=Ran+Ant+Qza+H_2O
Boyd, 1959, Res. Geochem., 1, 377-396	G	800-880°C/575-2000 bars	Tre=Olo+Ens+Qza+H_2O
Hewitt, O., 1975, Am. Min., 60, 391-397	G	460-681°C/2000-8000 bars	Phl+Ccl+Qza=Tre+San+CO_2+H_2O
Hoschek, 1973, Cont. Min. Pet., 39, 231-237	G	495-635°C/4000-6000 bars	Phl+Ccl+Qza=Tre+San+CO_2+H_2O
Metz, 1967, Geochim. Cosmo. Acta, 31, 1517-1532	G	450-550°C/500-1000 bars	Tre+Dol=For+Mcc+CO_2+H_2O
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	726-774°C/400 bars	Tre=Olo+Ens+Qza+H_2O
Wones & Dodge, 1977, Thermo. in Geol., 229-247	G	740-755°C/2000 bars	Tre+San=Phl+Olo+Qza
Adams & Williamson, 1923, J. Franklin Inst., 195, 475-529	V	25°C/2000-12000 bars	Tre
Stemple & Brindley, 1960, J. Am. Ceram. Soc., 43, 34-42	V		Tre
Sueno & others, 1973, Am. Min., 58, 649-664	V	24-700°C/1 atm	Tre
Wones & Dodge, 1977, Thermo. in Geol., 229-247	V	25°C/1 atm	Tre
Zussman, 1959, Acta Cryst., 12, 309-312	V		Tre

Wairakite

$CaAl_2Si_4O_{12}\cdot 2H_2O$ - Zeolite group

Wai

Important solid solution

(Ca,Na_2) Wairakite - Analcite join

$(H_2O, [])$ Wairakite - $CaAl_2Si_4O_{12}\cdot 2[]$ join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Juan & Lo, 1971, Proc. Geol. Soc. China, 14, 34-44	G	250-278°C/890-1380 bars	$Lau=Wai+H_2O$
Juan & Lo, 1971, Proc. Geol. Soc. China, 14, 34-44	G	292-469°C/690-1380 bars	$Wai=Ano+Qza+H_2O$
Liou, 1970, Cont. Min. Pet., 27, 259-282	G	325-393°C/500-5000 bars	$Wai=Ano+Qza+H_2O$
Liou, 1971, J. Pet., 12, 379-411	G	259-330°C/1000-6000 bars	$Lau=Wai+H_2O$
Liou, 1971, J. Pet., 12, 379-411	G	297-381°C/3200-4350 bars	Wai=Law+Qza
Lo, 1978, Proc. Geol. Soc. China, 21, 25-33	G	258-308°C/690-2069 bars	$Epi=Wai+Qza+H_2O$
Liou, 1970, Cont. Min. Pet., 27, 259-282	V	25°C/1 atm	Wai

Wollastonite $CaSiO_3$ - Pyroxene group Wol

Important solid solution

(Ca,Fe)	Wollastonite - Clinoferrosilite join
$(CaSi,Al_2)$	Wollastonite - Ca-Al Clinopyroxene join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Cristescu & Simon, 1934, Z. Phys. Chem., 258, 273-282	Cp	200-210 K/1 atm	Wol
Cristescu (in Wagner, 1932, Z. Anorg. Allg. Chem., 208, 1-22)	Cp	200-304 K/1 atm	Wol
Gronow & Schwiete, 1933, Z. Anorg. Allg. Chem., 216, 185-195	H_T-H_R	573-1373 K/1 atm	Wol
Roth & Bertram, 1929, Z. Elek. Angew. Phys. Chem., 35, 279-384	H_T-H_R	323-1157 K/1 atm	Wol
Southard, 1941, J. Am. Chem. Soc., 63, 3142-3146	H_T-H_R	485-1423 K/1 atm	Wol
Wagner, 1932, Z. Anorg. Allg. Chem., 208, 1-22	H_T-H_R	566-1383 K/1 atm	Wol
White, 1919, AJS, 2d ser., 47(277), 1-59	H_T-H_R	373-1573 K/1 atm	Wol
Hemingway & Robie, 1977, USGS J. Res., 5, 413-429	S	298.15 K/1 atm	Wol
Barany, 1966, US Bur. Mines Rpt. Inv. 6784, 8 p	H	346.85 K/1 atm	Wol=Qza+Lme
Charlu & others, 1978, Geochim. Cosmo. Acta, 42, 367-375	H	970 K/1 atm	Wol=Qzb+Lme
Kracek & others, 1953, Carn. Inst. Wash. Yb., 69-75	H	347.85 K/1 atm	Cwo=Wol
Nacken, 1930, Zement, 19, 818-825 & 847-849	H	314.85 K/1 atm	Cwo=Wol
Benz & Wagner, 1961, J. Phys. Chem., 65, 1308-1311	G(emf)	898-1148 K/1 atm	Wol=Qzb+Lme
Boettcher, 1970, J. Pet., 11, 337-379	G	893-1053 K/3000-5900 bars	Ano+Wol=Gro+Qzb
Gordon & Greenwood, 1971, Am. Min., 56, 1674-1688	G	700-849°C/2000 bars	$Ccl+Ano+Wol=Gro+CO_2$
Greenwood, 1967, Am. Min., 52, 1669-1680	G	558-595°C/1000-2000 bars	$Ccl+Qza=Wol+CO_2$
Greenwood, 1967, Am. Min., 52, 1669-1680	G	609-723°C/1000-2000 bars	$Ccl+Qzb=Wol+CO_2$
Gustafson, 1974, J. Pet., 15, 455-496	G	748-797°C/500-2000 bars	Adr+Fay=Mag+Wol+Qzb
Gustafson, 1974, J. Pet., 15, 455-496	G	789-839°C/500-2000 bars	Adr+Bun=Mag+Wol+Nic
Harker & Tuttle, 1956, AJS, 254, 239-256	G	600-800°C/300-2400 bars	$Ccl+Qzb=Wol+CO_2$

Haselton & others, 1978, Geophys. Res. Lett., 5, 753-756	G	1000-1325°C/10000-19000 bars	Cc2+Qzb=Wol+CO_2
Hays, 1965, Carn. Inst. Wash. Yb., 234-239	G	1473-1523 K/11000-14600 bars	Gro=Ano+Wol+Geh
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	725-825°C/1000-4000 bars	Ano+Wol+Ccl=Gro+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	755-788°C/1000 bars	Gro+Ccl=Geh+Wol+CO_2
Hoschek, 1974, Cont. Min. Pet., 47, 245-254	G	850-890°C/1000 bars	Ano+Ccl=Geh+Wol+CO_2
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	1125-1423 K/200-10000 bars	Gro=Ano+Wol+Geh
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	848-858 K/1000-3000 bars	Ano+Wol=Gro+Qza
Huckenholz, 1974, Carn. Inst. Wash. Yb., 411-426	G	888-958 K/4000 bars	Ano+Wol=Gro+Qzb
Liou, 1971, Am. Min., 56, 507-531	G	708-828 K/1974-5527 bars	Ano+Wol+H_2O=Pre
Liou, 1974, Am. Min., 59, 1016-1025	G	570-610°C/500-2000 bars	Adr+Qza+Fay=Hed+Wol
Liou. 1974, Am. Min., 59, 1016-1025	G	621-683°C/500-2000 bars	Adr+Qza+Nic=Hed+Wol+Bun
Newton, 1966, AJS, 264, 204-222	G	803-923 K/1100-2000 bars	Ano+Wol=Gro+Qza
Newton, 1966, AJS, 264, 204-222	G	973-1023 K/4700-5700 bars	Ano+Wol=Gro+Qzb
Shmulovich, 1974, Geochem. Int., 11, 883-887	G	1133-1153 K/500-700 atm	Gro=Ano+Wol+Geh
Shmulovich, 1977, Geochem. Int., 14, 126-134	G	627-727°C/1000-3920 bars	Ccl+Wol+Ano=Gro+CO_2
Evans, 1977, pers. comm., 1-5-77	V	25°C/1 atm	Wol
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Wol
Vaidya & others, 1973, JGR, 78, 6893-6898	V	25°C/5000-45000 bars	Wol
Rutstein, 1971, Am. Min., 56, 2040-2052	a	600-1000°C/1000 bars	Wol+Hed($CaSiO_3$-$CaFeSi_2O_6$ join)

Zoisite $Ca_2Al_3Si_3O_{12}(OH)$ - Epidote group

Important solid solution

(Al,Fe^{+3}) Zoisite - Epidote join

Reference	Data type	Range (Temperature/pressure)	Phases studied
Perkins & others, 1980, Geochim. Cosmo. Acta, 44, 61-84	Cp	200-298 K/1 atm	Zoi
Perkins & others, 1980, Geochim. Cosmo. Acta, 44, 61-84	Cp	298-730 K/1 atm	Zoi
Perkins & others, 1980, Geochim. Cosmo. Acta, 44, 61-84	S	298.15 K	Zoi
Boettcher, 1970, J. Pet., 11, 337-379	G	853-933 K/4000-5300 bars	Gro+Ano+H_2O=Zoi+Qza
Boettcher, 1970, J. Pet., 11, 337-379	G	898-928 K/3000 bars	Gro+Ano+Cor+H_2O=Zoi
Hewitt, D., 1973, Am. Min., 58, 785-791	G	539-540°C/6000 bars	Mus+Ccl+Qza=San+Zoi+CO_2+H_2O
Newton, 1965, J. Geol., 73, 431-441	G	843-1113 K/2000-6800 bars	Gro+Ano+Cor+H_2O=Zoi
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	340-385°C/4000-5000 bars	Law=Zoi+Kya+Pyr+H_2O
Nitsch, 1972, Cont. Min. Pet., 34, 116-134	G	370-430°C/7000 bars	Law+Qza=Zoi+Pyr+H_2O
Nitsch, 1974, For. Min., 51, 34-35	G	325-445°C/4000-10000 bars	Law=Zoi+Mar+Qza+H_2O
Storre & Nitsch, 1972, Cont. Min. Pet., 35, 1-10	G	510-700°C/2000-7000 bars	Zoi+CO_2=Ano+Ccl+H_2O
Strens, 1968, Min. Mag., 36, 864-867	G	770-823 K/2000 bars	Gro+Ano+H_2O=Zoi+Qza
Robie & others, 1967, USGS Bull. 1248, 87 p	V	25°C/1 atm	Zoi

Table 4.

Mineral phases, formulas, and codes used in tables 1, 2, and 3

Table 4. Mineral phases, formulas, & codes used in tables 1, 2, & 3

Code	Phases	Formula
Akt	Akermanite	$Ca_2MgSi_2O_7$
Alb	Albite, low	$NaAlSi_3O_8$
Alm	Almandine	$Fe_3Al_2Si_3O_{12}$
Ana	Analbite	$NaAlSi_3O_8$
Anl	Analcite	$NaAlSi_2O_6 \cdot H_2O$
And	Andalusite	Al_2SiO_5
Adr	Andradite	$Ca_3Fe_2Si_3O_{12}$
Ann	Annite	$KFe_3AlSi_3O_{10}(OH)_2$
Ano	Anorthite	$CaAl_2Si_2O_8$
Ant	Anthophyllite	$Mg_7Si_8O_{22}(OH)_2$
Atg	Antigorite	$Mg_{48}Si_{34}O_{85}(OH)_{62}$
Ara	Aragonite	$CaCO_3$
Boe	Boehmite	$AlO(OH)$
Bru	Brucite	$Mg(OH)_2$
Bun	Bunsenite	NiO
Cts	Ca-Al Clinopyroxene	$CaAl_2SiO_6$
Cc1	Calcite-I	$CaCO_3$
Cc2	Calcite-II	$CaCO_3$
Cal	Calcium	Ca
CO_2	Carbon dioxide	CO_2
Cga	Carnegieite, alpha	$NaAlSiO_4$
Cgb	Carnegieite, beta	$NaAlSiO_4$

Table 4. Continued

Code	Phases	Formula
Ctd	Chlorotoid	$FeAl_2SiO_5(OH)_2$
Chr	Chrysotile	$Mg_3Si_2O_5(OH)_4$
Cln	Clinochlore	$Mg_5Al_2Si_3O_{10}(OH)_8$
Cen	Clinoenstatite	$MgSiO_3$
Cfs	Clinoferrosilite	$FeSiO_3$
Czo	Clinozoisite	$Ca_2Al_3Si_3O_{12}(OH)$
Crd	Cordierite	$Mg_2Al_4Si_5O_{18}\cdot H_2O$
Cor	Corundum	Al_2O_3
Cra	Cristobalite, alpha	SiO_2
Crb	Cristobalite, beta	SiO_2
Cwo	Cyclowollastonite	$CaSiO_3$
Dia	Diaspore	$AlO(OH)$
Dic	Dickite	$Al_2Si_2O_5(OH)_4$
H_2O	Dihydrogen oxide	H_2O
Dio	Diopside	$CaMg(SiO_3)_2$
Dol	Dolomite	$CaMg(CO_3)_2$
Ens	Enstatite	$MgSiO_3$
Ept	Epidote	$Ca_2FeAl_2Si_3O_{12}(OH)$
Epi	Epistilbite	$CaAl_2Si_6O_{16}\cdot 5H_2O$
Fay	Fayalite	Fe_2SiO_4
Fec	Fe-Cordierite	$Fe_2Al_4Si_5O_{18}\cdot H_2O$
Fgh	Ferrigehlenite	$Ca_2Fe_2SiO_7$

Table 4. Continued

Code	Phases	Formula
Fes	Ferrosilite	$FeSiO_3$
For	Forsterite	Mg_2SiO_4
Geh	Gehlenite	$Ca_2Al_2SiO_7$
Gib	Gibbsite	$Al(OH)_3$
Gra	Graphite	C
Gro	Grossular	$Ca_3Al_2Si_3O_{12}$
Hal	Halloysite	$Al_2Si_2O_5(OH)_4$
Hed	Hedenbergite	$CaFe(SiO_3)_2$
Hem	Hematite	Fe_2O_3
Hcy	Hercynite	$FeAl_2O_3$
Heu	Heulandite	$Ca(Al_2Si_7O_{18})\cdot 6H_2O$
Ill	Illite	$(K,H_3O)_{x+y}(Mg,Fe)_x$ $Al_{2-x+y}Si_{4-y}O_{10}(OH)_2\cdot$ $(\_x-y-z)H_2O$ $x+y+z < 1$
Ilm	Ilmenite	$FeTiO_3$
Irn	Iron	Fe
Jad	Jadeite	$NaAl(SiO_3)_2$
Klp	Kaliophilite	$KAlSiO_4$
Kal	Kalsilite	$KAlSiO_4$
Kao	Kaolinite	$Al_2Si_2O_5(OH)_4$
Kya	Kyanite	Al_2SiO_5

Table 4. Continued

Code	Phases	Formula
Lar	Larnite	Ca_2SiO_4
Lau	Laumontite	$CaAl_2Si_4O_{12} \cdot 4H_2O$
Law	Lawsonite	$CaAl_2Si_2O_7(OH)_2 \cdot H_2O$
Leo	Leonhardite	$Ca_2Al_4Si_8O_{24} \cdot 7H_2O$
Leu	Leucite	$KAlSi_2O_6$
Lme	Lime	CaO
Mag	Magnesite	$MgCO_3$
Mcc	Magnesiocalcite	$(Ca,Mg)CO_3$
Mgt	Magnetite	Fe_3O_4
Mar	Margarite	$CaAl_4Si_2O_{10}(OH)_2$
Mei	Meionite	$Ca_4Al_6Si_6O_{25} \cdot CO_2$
Mer	Merwinite	$Ca_3Mg(SiO_4)_2$
Mic	Microcline	$KAlSi_3O_8$
Mal	Monalbite	$NaAlSi_3O_8$
Mtc	Monticellite	$CaMgSiO_4$
Mus	Muscovite	$KAl_3Si_3O_{10}(OH)_2$
Nmt	Na-Beidellite	$Na_{.33}Al_2[Al_{.33}Si_{3.67}]O_{10}(OH)_2$
Nat	Natrolite	$Na_2Al_2Si_3O_{10} \cdot 2H_2O$
Nep	Nepheline	$NaAlSiO_4$
Nic	Nickel	Ni
Ofs	Orthoferrosilite	$FeSiO_3$
Par	Paragonite	$NaAl_3Si_3O_{10}(OH)_2$

Table 4. Continued

Code	Phases	Formula
Per	Periclase	MgO
Phl	Phlogophite	$KMg_3AlSi_3O_{10}(OH)_2$
K20	Potassium oxide	K_2O
Pre	Prehnite	$Ca_2Al_2Si_3O_{10}(OH)_2$
Pen	Protoenstatite	$MgSiO_3$
Pfs	Protoferrosilite	$FeSiO_3$
Pyt	Pyrite	FeS_2
Pyp	Pyrope	$Mg_3Al_2Si_3O_{12}$
Pyr	Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$
Pyo	Pyrrhotite	$Fe_{1-x}S$
Qza	Quartz, alpha	SiO_2
Qzb	Quartz, beta	SiO_2
Ran	Rankinite	$Ca_3Si_2O_7$
Rut	Rutile	TiO_2
San	Sanidine	$KAlSi_3O_8$
Sid	Siderite	$FeCO_3$
Hsi	"Silicic acid"	H_4SiO_4
Sil	Sillimanite	Al_2SiO_5
N20	Sodium oxide	Na_2O
Spl	Spinel	$MgAl_2O_4$
Sta	Staurolite	$Fe_2Al_9Si_4O_{23}(OH)$
H_2O	Steam	H_2O

Table 4. Continued

Code	Phases	Formula
Stl	Stilbite	$CaAl_2Si_2O_{18}\cdot7H_2O$
Tlc	Talc	$Mg_3Si_4O_{10}(OH)_2$
Tre	Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$
Wai	Wairakite	$CaAl_2Si_4O_{12}\cdot2H_2O$
H_2O	Water	H_2O
Wol	Wollastonite	$CaSiO_3$
Wus	Wustite	$Fe_{1-x}O$
Zoi	Zoisite	$Ca_2Al_3Si_3O_{12}(OH)$

Table 5.

List of abbreviations used for journals

Table 5. List of abbreviations used for journals

Abbreviated reference	Full reference
AJS	American Journal of Science
Acta Cryst.	Acta Crystallographica
Am. Cryst. Assoc. Mon.	American Crystallographic Association Monograph
Am. Min.	American Mineralogist
Ann. pour l'an Paris, Bur. longitudes	Annuaire pour l'an (1888) Paris, Bureau des longitudes
Ber. Bunsenges. Physik. Chem.	Berichte der Bunsengesellschaft fur Physikalische Chemie
Bull. Soc. Fr. Min. Crist.	Bulletin de la Societe Francaise de Mineralogie et de Cristallographie
CODATA Bull.	CODATA Bulletin
Can. J. Earth Sci.	Canadian Journal of Earth Sciences
Can. Min.	Canadian Mineralogist
Carn. Inst. Wash. Yb.	Carnegie Institute of Washington Yearbook
Cont. 9th Int. Conf. Prop. Steam, Munich	Contributions to the 9th International Conference on the Properties of Steam, Munich, 1979
Cont. Min. Pet.	Contributions to Mineralogy and Petrology
Dokl. Akad. Nauk SSSR	Doklady Akademiia Nauk SSSR
EOS	Transactions of the American Geophysical Union. EOS
Earth Planet. Sci. Lett.	Earth and Planetary Science Letters
Econ. Geol.	Economic Geology
Faraday Trans.	Journal of the Chemical Society, London, Faraday Transactions
Finland Comm. Geol. Bull.	Bulletin de la Commission Geologique de Finlande
For. Min.	Fortschritte der Mineralogie
GSA Abs. Prog.	Geological Society of America Abstracts with Programs
GSA Mem.	Geological Society of America Memoirs
Geochem. Int.	Geochemistry international
Geochim. Cosmo. Acta	Geochimica et Cosmochimica Acta
Geokhim.	Geokhimiia

Table 5. List of abbreviations used for journals

Abbreviated reference	Full reference
Geophys. Res. Lett.	Geophysical Research Letters
Inorg. Chem.	Inorganic Chemistry
Izmer. Tekh.	Izmeritel'naya Tekhnika
J. Am. Ceram. Soc.	Journal of the American Ceramic Society
J. Am. Chem. Soc.	Journal of the American Chemical Society
J. Appl. Phys.	Journal of Applied Physics
J. Chem. Thermodyn.	Journal of Chemical Thermodynamics
J. Chim. Phys.	Journal de Chimie Physique et de Physico-Chimie Biologique
J. Franklin Inst.	Journal of the Franklin Institute
J. Geol.	Journal of Geology
J. Inorg. Nuc. Chem.	Journal of Inorganic and Nuclear Chemistry
J. Iron Steel Inst.	Journal of the Iron and Steel Institute
J. Pet.	Journal of Petrology
J. Phys. Chem. Ref. Data	Journal of Physical and Chemical Reference Data
J. Phys. Chem. Solids	Journal of Physics and Chemistry of Solids
J. Phys. Chem.	Journal of Physical Chemistry
J. Res. NBS	Journal of Research of the National Bureau of Standards
J. Sci. Res. Banaras Hindu Univ., India	Journal of Scientific Research of the Banaras Hindu University, India
JANAF	JANAF, National Standard Reference Data Series
JANAF, Nat. Std. Ref. Data Ser.	JANAF, National Standard Reference Data Series
JGR	Journal of Geophysical Research
Japan. J. Geol. Geog.	Japanese Journal of Geology and Geography
Kristall.	Kristallografiia
Lithos	Lithos
Meas. Tech.	Measurement Techniques

Table 5. List of abbreviations used for journals

Abbreviated reference	Full reference
Mem. Sci. Rev. Metal.	Memoires Scientifiques de la Revue de Metallurgie
Sel. Val. Thermo. Prop. Elem.	Selected Values of the Thermodynamic Properties of the Elements
Min. J. (Tokyo)	Mineralogical Journal (Tokyo)
Min. Mag.	Mineralogical Magazine
Moscow Univ. Geol. Bull.	Moscow University Geology Bulletin
Nature	Nature
Naturw.	Naturwissenschaften
Neorg. Mater.	Izvestiia Akademii Nauk SSSR, Neorganicheskie Materialy
Neues Jahrb. Min., A.	Neues Jahrbuch fur Mineralogie, Abhandlungen
Neues Jahrb. Min., M.	Neues Jahrbuch fur Mineralogie, Monatshefte
Ocherki Fiz.-Khim. Pet.	Ocherki Fiziko-Khimicheskoi Petrologii
Pers. comm.	Personal communication
Phys. Chem. Glasses	Physics and Chemistry of Glasses
Phys. Earth Planet. Int.	Physics of the Earth and Planetary Interiors
Proc. Phys. Soc., London	Proceedings of the Physical Society, London
Proc. Geol. Soc. China	Proceedings of the Geological Society of China
Proc. Imp. Acad. (Tokyo)	Proceedings of the Imperial Academy (Tokyo)
Proc. Indian Acad. Sci.	Proceedings - Indian Academy of Sciences
Proc. NATO Adv. Study Inst.	Proceedings of the NATO Advanced Study Institute Series
Proc. Nat. Acad. Sci.	Proceedings of the National Academy of Sciences (U.S.)
Proc. Roy. Soc. London	Proceedings of the Royal Society of London
Prog. Astronau. Aeronau.	Progress in Astronautics and Aeronautics
Prog. Exp. Pet.	Progress in Experimental Petrology
Res. Geochem.	Researches in Geochemistry
Rpt. Brit. Admir.	Report to the British Admiralty

Table 5. List of abbreviations used for journals

Abbreviated reference	Full reference
Russ. J. Inorg. Chem.	Russian Journal of Inorganic Chemistry
Russ. J. Phys. Chem.	Russian Journal of Physical Chemistry
Schweiz. Min. Petrogr. Mitt.	Schweizerische Mineralogische und Petrographische Mitteilungen
Sci.	Science
The Feldspars, NATO Adv. Study Inst.	The Feldspars, NATO Advances Study Institute Series
Thermo. in Geol.	Thermodynamics in Geology
Trans. Brit. Ceram. Soc.	Transactions of the British Ceramic Society
Trans. Metal. Soc. AIME	Transactions of the Metallurgical Society of AIME
Tsch. Min. Pet. Mitt.	Tschermaks Mineralogische und Petrographische Mitteilungen
US Bur. Mines Bull.	U.S. Bureau of Mines Bulletin
US Bur. Mines Rpt. Inv.	U.S. Bureau of Mines Report of Investigations
US NBS Circ.	U.S. National Bureau of Standards Circular
US NBS Interim Rpt.	U.S. National Bureau of Standards Interim Report
US NBS J. Res.	U.S. National Bureau of Standards Journal of Research
US NBS NSRDS-NBS	U.S. National Bureau of Standards, National Standard Reference Data Series
US NBS Tech. Note	U.S. National Bureau of Standards Technical Note
USGS Bull.	U.S. Geological Survey Bulletin
USGS J. Res.	U.S. Geological Survey Journal of Research
USGS Prof. Paper	U.S. Geological Survey Professional Paper
Wash. Acad. Sci. J.	Journal of the Washington Academy of Sciences
Z. Anorg. Allg. Chem.	Zeitschrift fur Anorganische und Allgemeine Chemie
Z. Anorg. Chem.	Zeitschrift fur Anorganische Chemie
Z. Elek.	Zeitschrift fur Elektrochemie
Z. Elek. Angew. Phys. Chem.	Zeitschrift fur Elektrochemie und Angewandte Physikalische Chemie
Z. Krist.	Zeitschrift fur Kristallographie

Table 5. List of abbreviations used for journals

Abbreviated reference	Full reference
Z. Phys. Chem.	Zeitschrift fur Physikalische Chemie
Zement	Zement

APPENDIX II

SECTION 1.

FEASIBILITY STUDY

DATA FOR NUCLEAR WASTE DISPOSAL

THE MECHANICAL PROPERTIES OF BASALT, GRANITE, SHALE, AND TUFF

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This is a report covering the data on the mechanical properties of basalt, granite, shale, and tuff. The properties covered are briefly defined and their respective peculiarities are discussed. Some statistics are presented for each rock system and property describing the data known to exist in the literature. Typical examples of the data in both tabular and graphical form are also presented. The report provides a most exhaustive bibliography on the subject of the report.

This report reviews the feasibility for proceeding with a more comprehensive study and evaluation of the mechanical properties of the four rock systems. A companion report treats the thermal and electrical properties of these same rocks.

TABLE OF CONTENTS

GENERAL SYMBOLS

ε	strain
$\dot{\varepsilon}$	strain rate
σ	normal stress
σ_1	major principal stress
σ_3	minor principal stress
τ	shear stress
P_m	mean stress
μ	Poisson's ratio
K	bulk modulus
1/K	compressibility
G	shear modulus; modulus of rigidity
E	Young's modulus; modulus of elasticity
V_p	longitudinal wave velocity; P wave velocity
V_s	shear wave velocity; S wave velocity
k	permeability
p	porosity
ρ	density
H	hardness

DATA TABLE SYMBOLS

P	pressure, MPa
p	porosity, %
R	test in bending, MPa
T	tangent modulus at 50% fracture strength
w	water, %
⊥	right angle to
//	parallel to
*	dynamic test values
**	saturated or wet
-	location not known
D	differential stress, MPa
S	stress, MPa

GENERAL INTRODUCTION

This report surveys the data available in the literature on the mechanical properties of four major rock types with a view to their potential use as nuclear waste disposal depositories.

Specific guidelines as to the nature of the properties required have been supplied by the National Bureau of Standards and as far as possible these guidelines have been adhered to.

A total of about 1100 possible abstracts were retrieved from computer search files and were visually screened. Of these, a total of approximately 230 documents were selected and were further examined in detail. In this report the number of references is presented property by property and, therefore, the number of references per property varies. In addition, at this time the number of salient documents is presented rather than the number of data sets. This can be misleading since, though a property may have only a few references, the amount of data presented may be extensive.

It is the nature of data surveys that much, if not all, of the information collected is the work of others. This report and its final form are no exception and in many cases certain works are heavily drawn upon. In particular, attention is drawn to the work of Lama et al. cited in reference [115].

At present, in this report property data for four rock types is presented as well as a general indication of the state-of-the-art and the number of references that will be utilized. The format of the data presentation is both graphical and tabular, with more emphasis being placed on the latter format since it is the most common form in the published literature.

Four rock types, namely: basalt, granite, shale, and tuff, have been considered and in extracting data, petrological definitions of these rocks have been strictly adhered to as far as possible. These definitions are given below as obtained from reference [107].

<u>Basalt</u>: an extrusive, fine-grained rock composed primarily of calcic plagioclase with or without olivine.

<u>Granite</u>: a plutonic rock consisting essentially of alkali feldspar and quartz.

Shale: a laminated sediment in which the constituent particles are of predominantly clay grade. This includes indurated, laminated, or fissile claystones and siltstones.

Tuff: a rock composed of compacted volcanic fragments less than 4 mm in diameter.

For the purposes of this report, partial data has been provided as an example for the four rock types. Geologically more common rocks such as granite and basalt are much more fully represented in the literature and consequently the amount and type of data is far more extensive than for less common types. Relevant data accompanies each property and appears after the discussion provided for that property or group of properties. Unless otherwise indicated, all data are laboratory values.

PROPERTIES

Density

This property is defined as the mass per unit volume. The volume, however, varied depending on what phase of the naturally occurring rock is considered. The solid phase obviously has a different volume than the solid phase + gas phase, for example. If one takes into account the three possible phases that coexist in natural rock, i.e., solid, liquid, and gas, it becomes apparent that several definitions of density are possible and, in fact, do exist. These are divided into "true," "apparent," and "bulk" determinations.

"True" determinations take into account the volume of only the solid phase of the rock with respect to the mass of the rock.

"Apparent" determinations use the dry (solid + gas) mass of a unit volume of solids.

"Bulk" determinations use the prevailing conditions (solid + liquid + gas) of the rock to determine the mass of a unit volume of rock.

"Specific gravity" is, for practical purposes, a relative density with respect to water.

"Grain density," as the name implies, is a density determination in which the mass of the grains of the rock and the volume of these grains are utilized.

A problem with published literature at present is that most often the type of density is not stated - the value is merely quoted. Generally, it appears wise to presume that densities given are "apparent" values. The same applies to specific gravities.

The various densities can be obtained using the "pycnometric," "buoyancy," or "direct measurement" techniques. In the case of the first two, both use pycnometers and are applications of Archemedes principle. Of these methods, the "buoyancy" method is the most accurate.

TABLE 1.

DENSITY DATA STATISTICS

Rock Type	No. of Documents
Granite	52
Basalt	39
Tuff	17
Shale	16

Elastic Properties

The elastic properties considered here are:

Young's modulus (secant and/or tangent)
Bulk modulus
Shear modulus
Poisson's ratio
Compressibility (the reciprocal of the bulk modulus)
Wave velocities

The determination of the above properties can be static (with exception of wave velocities) or dynamic, and either laboratory or in-situ. Overall, in both in-situ and laboratory tests it is important to be able to measure load stresses and deformation accurately and be able to minimize or remove factors which lead to erroneous or distorted values.

Dynamically obtained elastic constants tend to be higher than those obtained statically; however, they are of importance when one needs to know the behavior of rock subjected to shock loading.

Basically, elastic constants achieved by static methods are indicative of large strains, e.g., 10^{-3}, which occur in mining. Dynamic methods investigate lower strains of 10^{-5}. Static methods give rise to larger scatter of results, while dynamic methods give rise to less.

Dynamic Constants

These constants are calculated from elastic wave velocities and density. In-situ seismic reflection or refraction can be used with refraction being the more popular. Laboratory values are determined using either the ultrasonic or resonance techniques.

For the purposes of this work, two kinds of waves are considered; namely: P or compression and S or shear waves. Both of these are body waves, i.e., transmitted through (rather than along the surface) the body. Compressional waves cause longitudinal particle oscillation, while shear waves cause transverse oscillation.

In the case of the laboratory methods mentioned, the basic difference between the two is the frequency at which the velocities are determined. The excitation frequency, however, has been shown to have no effect on the wave velocities, but a significant effect on the calculation of Poisson's ratio.

Wave velocities, like other properties, are affected by various factors. Briefly, these factors are:

1) Rock type
2) Texture (grain size is important)
3) Density (density and average atomic weight dictate velocity of longitudinal waves)
4) Porosity (velocity decreases with increasing porosity)
5) Anisotropy (velocity parallel to layers greater than velocity perpendicular to layers)
6) Water content (generally water saturation increases velocity in hard rocks)
7) Temperature (velocity of longitudinal waves decreases with increase in temperature)

Static Constants

In-situ values are generally obtained by one of the following methods:

Plate bearing tests
Pressure tunnel tests
Borehole tests

These are all large scale tests and are expensive to perform. The specifics of such tests vary depending on the conditions encountered.

Laboratory values are obtained by several methods. Some of the commonly used methods are:

Simple Direct Compression or Tension Test: In these tests prismatic specimens are loaded in compression or tension.

Bending Tests: Young's modulus can be determined using 3 or 4 point loading of a beam.

Brazilian Test: Poisson's ratio and Young's modulus can be obtained by measuring the strains at the center of a loaded disk in both vertical and horizontal directions.

Triaxial Test: Solid and hollow specimens can be loaded triaxially and deformations can be measured. These stresses and deformations can then be utilized to find Young's modulus.

All the elastic constants are related to one another provided one assumes a perfectly elastic, isotropic, homogeneous material. Rock seldom fulfills these conditions; however, in certain instances, it may be close enough to allow approximate fulfillment of these assumptions.

Moduli in tension and compression are not the same and may vary from 1 to 10 times or more. Variations of moduli with stress are due to changes occurring in the structure of rocks during loading and unloading. Comparison of in-situ and laboratory values indciate a good deal of difference in many cases and this discrepancy is a function of discontinuities present in the in-situ condition.

TABLE 2.

ELASTIC PROPERTIES DATA STATISTICS

Property	No. of Documents			
	Granite	Basalt	Tuff	Shale
<u>Static Properties</u>				
Young's modulus	51	28	18	24
Bulk modulus	9	9	1	0
Shear modulus	9	7	2	0
Poisson's ratio	30	21	14	14
Compressibility	9	9	1	0
<u>Dynamic Properties</u>				
Young's modulus	17	8	6	10
Bulk modulus	6	1	0	0
Shear modulus	8	3	3	4
Poisson's ratio	8	4	2	3
Compressibility	6	1	0	0
Wave velocities	9	10	5	1

Discussion of Elastic Properties Data (Part A)

A sample of the tabular data for all the rock types are presented in the following pages.

Figure 1 is reproduced as an example of the curve data. The curve of Young's Modulus versus confining pressure (Fig. 1) was determiend on samples from Units 3 and 4a of Diamond Dust Tuff. Samples were obtained from various depths in boreholes. Dynamically obtained modulus values at confining pressures below 0.3 MPa can be expected to be higher than in-situ field or static measurements by as much as several hundred percent. This discrepancy is due to fractures and grain boundary effects.

There is no consistent value for Young's Modulus for all samples; however, above confining pressures of 0.4 MPa the modulus values obtained are in reasonable agreement with statically obtained values.

DENSITY AND ELASTIC PROPERTIES

PART A

Density	ρ
Modulus of Elasticity	E
Modulus of Rigidity	G
Poisson's Ratio	ν

TABLE 3

DENSITY AND ELASTIC PROPERTIES (PART A)

Rock Type and Location	Density $\rho(g/cm^3)$	Modulus of Elasticity E(GPa)	Modulus of Rigidity G(GPa)	Poisson's Ratio ν	Remarks	Ref. No.
Basalt; Ostrich, Germany	-	11.2	-	-	p = 10-90	50
Basalt; Champion Mine, MI	2.85	61	27	-		128
	2.97	85	34	-		128
Basalt; Howard Prairie Dam, OR	2.74	63	-	0.25	p = 0-7, altered	128
	2.74	61	-	0.22	p = 0-35	128
	2.82	76.4	31.5	0.22	p = 0.1	60
	2.82	82.5	33.0	0.25	p = 100	60
Basalt; Guadalupe drill site	2.82	48.5	-	0.38		119
Basalt; Medford, OR	2.72	60	-	0.22	p = 0-41.6	129
	2.74	-	-	-	p = 0-41.6	129
Basalt; MI	2.85	96	38	0.281	Altered	129
	2.70	41	18	0.09	Altered, amygdaloidal	129
	2.8	60.0	-	0.15	Heavily altered, amygdaloidal	129
Basalt; Koyna Dam, India	2.54	36.20	-	0.13	Altered, vesicular	48
Granite; Mitidieri, Quarry, Brazil	2.68	69.6	-	0.24	Porphyritic	108
Granite; Valinhos, Quarry, Brazil	2.56	65.8	-	0.18		108
Granite; Cantareira, Quarry, Brazil	2.75	64.1	-	0.25		108
Surmaline-Granite; Piccicacco, Quarry, Brazil	2.62	75.5	-	0.16		108
	-	70.3	-	0.30		63
	-	58.6	-	0.20		63
	-	71.0	-	0.25		63
Granite; AEC, Nevada test site	2.69	73.8	-	0.22	Dense, unweathered, at 50% of failure	120

DENSITY AND ELASTIC PROPERTIES (PART A) (Continued)

Rock Type and Location	Density $\rho(g/cm^3)$	Modulus of Elasticity E(GPa)	Modulus of Rigidity G(GPa)	Poisson's Ratio ν	Remarks	Ref. No.
Granite; Grand Coulee, WA	2.61	7.79	-	0.13	Slightly altered	36
Granite; Pole Hill, USA	2.62	19.0	-	0.09	Pegmatite	36
Granite; Pikes Peak, USA	2.67	33.4	-	0.37	Weathered, at 50% of failure	93
	2.64	70.6	-	0.18	Dense, at 50% of failure	93
Tuff; Kirkland, Ont., Canada	2.78	86.87	32.41	-	p = 1.5	128
Tuff	2.0	15.6	-	0.09	Yellow, w = 17.5	56
	1.60	6.34	-	0.15	Red and yellow, w = 4.6	56
Tuff; NTS-E Tunnel, USA	1.61	5.03	-	0.21		93
Tuff; Lakeshore, Canada	-	76.53	31.03	0.23		96
Tuff; Helen Mine, Canada	-	82.74	-	0.27	Vertical	96
Lithic Tuff; Medowell Dam, AZ	-	1.38	-	-	Altered	48
Lapilli Tuff; AEC Nevada test site	-	9.71	-	0.10	Variable pore size	132
Tuff; Soledad Dam, Mexico	1.9	1.7	-	-	Seismic, field	123
	2.2	2.7	-	-	Seismic, field	123
Tuff; Green Peters Dam, USA	-	7.0	-	0.20		57
Tuff; AEC Nevada test site	-	3.72	-	0.19		121
Tuff; Seikan Tunnel, Japan	2.19	-	-	-		95
Shale	2.21	21.9	-	0.18	p = 16.2	77
Shale (calcareous); Marble Canyon Dam, AZ	2.67	12.41 24.48	15.86	0.04	p = 1.8, 0-70 bars	36
Shale (quartzose); Marble Canyon Dam, AZ	2.69	13.79 22.06	11.72	0.07	p = 6.6	36

DENSITY AND ELASTIC PROPERTIES (PART A) (Continued)

Rock Type and Location	Density $\rho(g/cm^3)$	Modulus of Elasticity E(GPa)	Modulus of Rigidity G(GPa)	Poisson's Ratio ν	Remarks	Ref. No.
Shale; Murdock, IL	-	7.52	-	0.103		129
Shale; Utah	2.81	58.19	26.61	0.09	p = 0.9	129
	2.80	68.05	30.47	0.12	p = 0.57	129
	2.92	65.71	28.06	0.17	p = 0.62	129
Shale; Monticello Dam, CO	2.50	13.0	12.0	0.12	p = 0-14	125
		27.0				
Shale; W.A.C. Bennett Dam, NS, Canada	-	38.6	-	-		76
	-	30.4	-	-		76
	-	36.5	-	-		76
Sandy Shale; Upper Silesia, Poland	-	54.7	-	-	$\perp$ bedding	46
	-	63.7	-	-	// bedding	46

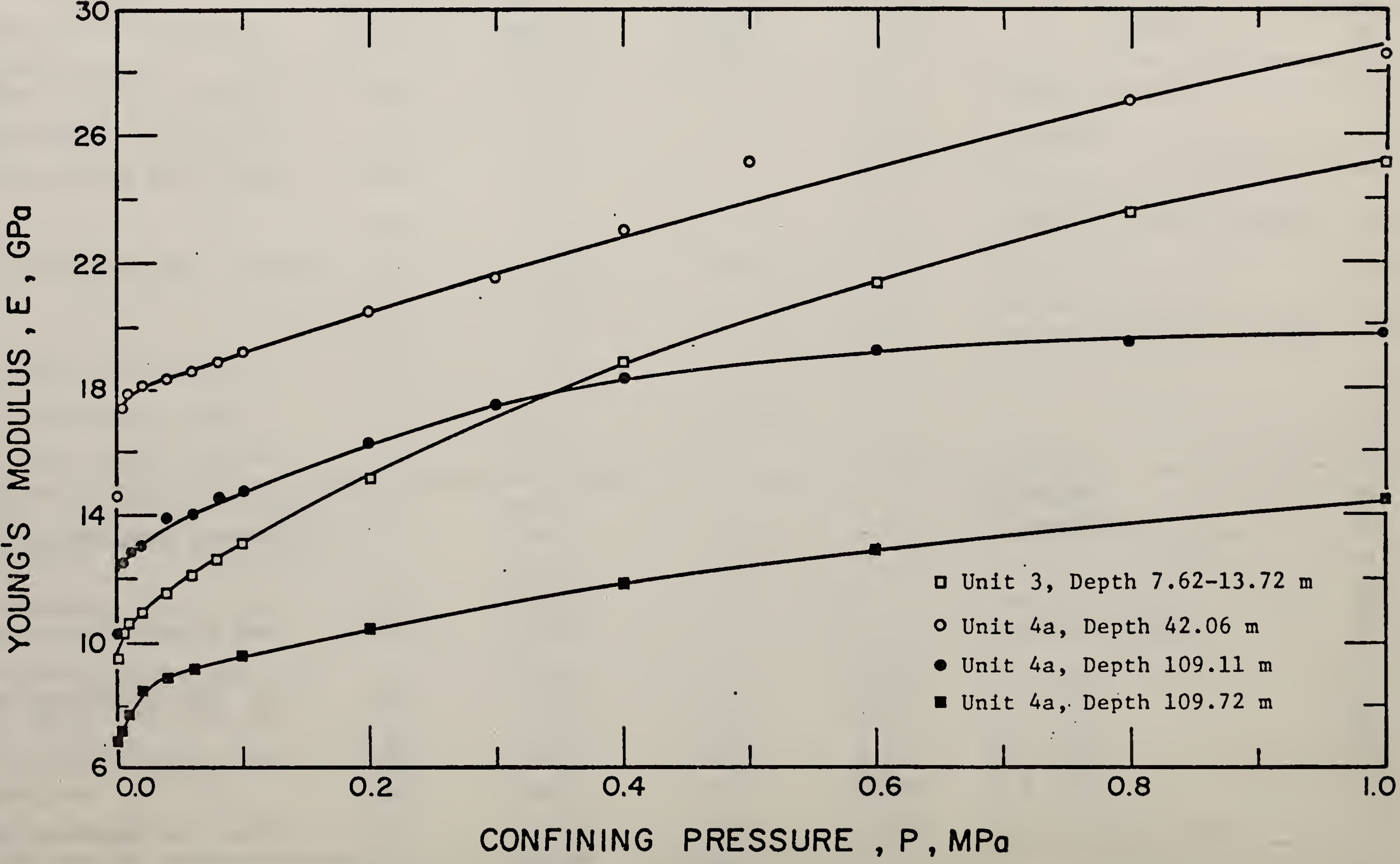

Figure 1. Confining Pressure vs Young's Modulus for Diamond Dust Tuff [10].

Discussion of Elastic Properties Data (Part B)

Granite and basalt are represented in the sample tabular data. No such data have been retrieved on shale or tuff.

Sample curve data for shale are presented in Figure 2. Cylindrical drill samples 3.81 cm in diameter and 2.54 cm long were tested after being oven dried for 48 hours at 366 K. Specimens were enclosed with neoprene jacket and transducers attached to each end, the system then sealed in a pressure cell and confining pressures achieved by the system were of the order of 70 MPa.

As can be seen from the curve, initially dry Green River shale has a higher compressibility than its water saturated counterpart. The trend for both wet and dry samples not unexpectedly shows decreasing compressibility with increasing confining pressure.

DENSITY AND ELASTIC PROPERTIES

PART B

Density	ρ
Bulk Modulus	K
Compressibility	$\frac{1}{K}$

TABLE 4.

DENSITY AND ELASTIC PROPERTIES (PART B)

Rock Type and Location	Density $\rho(g/cm^3)$	Bulk Modulus K(GPa)	Compressibility $1/K(GPa^{-1})$	Remarks	Ref. No.
Granite; Westerly, RI	-	-	0.020	p = 0.1, unenclosed	81
	-	-	0.033	p = 60, unenclosed	33
	2.628	-	0.023	p = 3.4, enclosed	187
	2.628	-	0.018	p = 34.5, enclosed	187
	2.628	-	0.017	p = 103, enclosed	187
	2.615	-	0.020	p = 50, enclosed	184
	2.615	-	0.018	p = 500, enclosed	184
	2.616	-	0.021	p = 200, unenclosed	196
	2.616	-	0.018	p = 1000, unenclosed	196
	2.616	-	0.018	p = 400, enclosed	195
	2.646	-	0.083	p = 0.1, enclosed	149
	2.646	-	0.029	p = 50, enclosed	149
	2.646	-	0.025	p = 100, enclosed	149
	2.646	-	0.022	p = 200, enclosed	149
	2.646	-	0.020	p = 500, enclosed	149
	2.646	-	0.019	p = 900, enclosed	149
Granite; Bear Mt., TX	2.610	-	0.021	p = 3.4, enclosed	187
	2.610	-	0.018	p = 34.5, enclosed	187
Basalt; DSDP leg 34	-	57.0	0.017	p = 40	29
	-	59.0	0.017	p = 100	29
	-	60.0	0.017	p = 200	29
	-	63.0	0.016	p = 600	29
Basalt; DSDP leg 39	-	51.0	-	p = 40	31
	-	52.0	-	p = 100	31
	-	53.0	-	p = 200	31
	-	57.0	-	p = 600	31
Basalt; DSDP leg 39	-	53.0	-	p = 40	31
	-	54.0	-	p = 100	31
	-	55.0	-	p = 200	31
	-	58.0	-	p = 600	31

DENSITY AND ELASTIC PROPERTIES (PART B) (Continued)

Rock Type and Location	Density $\rho(g/cm^3)$	Bulk Modulus K(GPa)	Compressibility $1/K(GPa^{-1})$	Remarks	Ref. No.
Basalt; DSDP leg 39	-	59.0	-	p = 40	31
	-	59.0	-	p = 100	31
	-	59.0	-	p = 200	31
	-	59.0	-	p = 600	31
Basalt; DSDP leg 39	-	68.0	-	p = 40	31
	-	68.0	-	p = 100	31
	-	58.0	-	p = 200	31

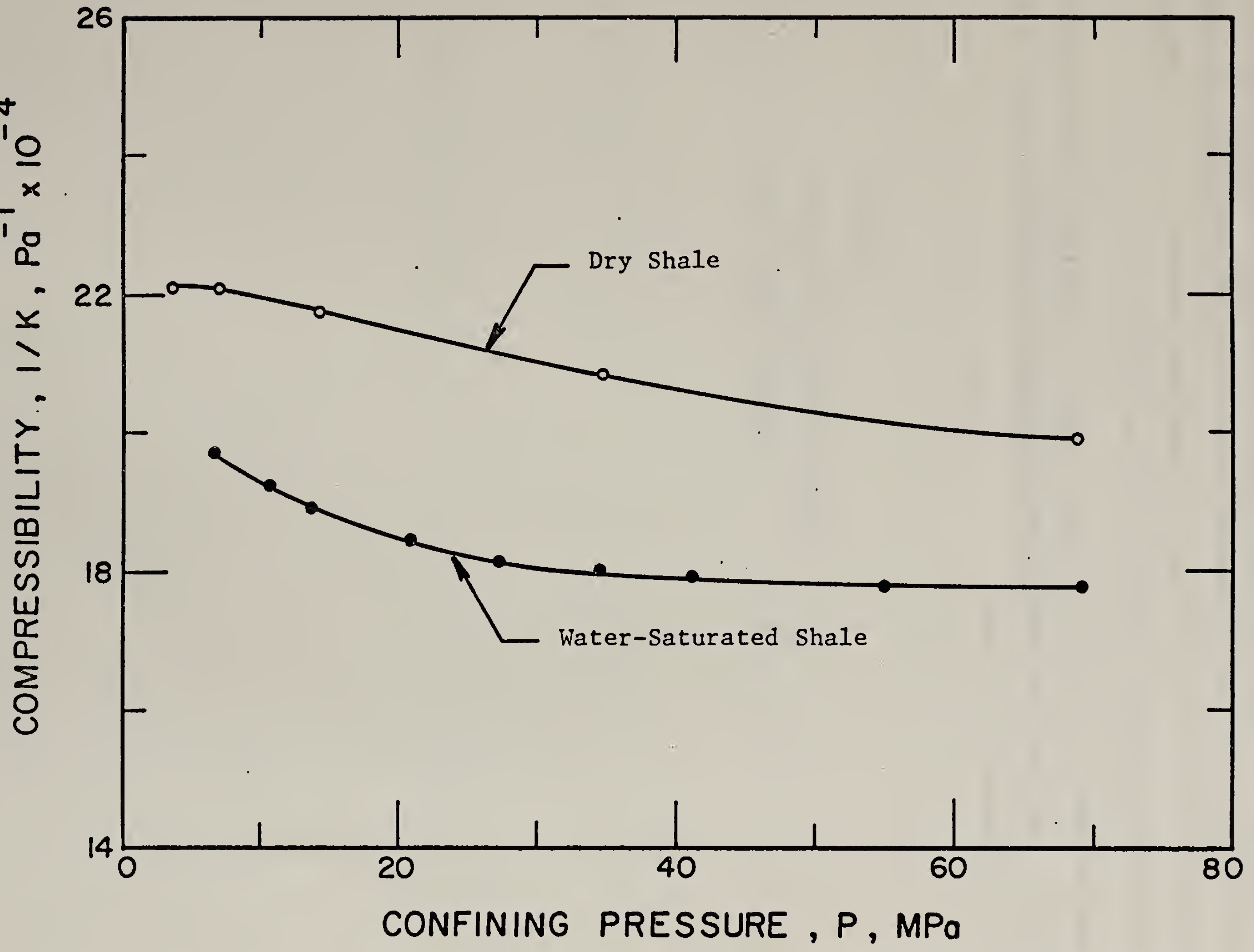

Figure 2. Compressibility vs Confining Pressure for Dry and Water-Saturated Green River Shale [11].

Discussion of Elastic Properties Data (Part C)

Sample tabular data are presented for all four rock types in the following pages.

Figure 3 represents a sample of the curve data. Specimens of Westerly and Troy Granite, 1.3 cm in diameter and 2.5 cm long, were used to measure shear and compressional wave velocities for confining pressures of 0.1 MPa and 40 MPa for temperatures ranging from about 245 to 275 K.

Samples were saturated with water near the melting point of ice after being oven dried. Temperatures during the tests were accurate to ±0.5 K whilst pressures were accurate to ±1 MPa.

DENSITY AND ELASTIC PROPERTIES

PART C

Density	ρ
Longitudinal Wave Velocity	V_p
Shear Wave Velocity	V_s

TABLE 5.

DENSITY AND ELASTIC PROPERTIES (PART C)

Rock Type and Location	Density $\rho(g/cm^3)$	Pressure MPa	V_p km/sec	V_s km/sec	Remarks	Ref. No.
Montello Granite	2.64	-	5.27	3.18	Surface	1
	2.64	-	4.65	3.04	Core	1
Granite; Conway, NH	2.786	0.1	5.01	2.78		147
	2.786	10	5.06	2.80		147
	2.786	40	5.16	2.83		147
	2.786	100	5.24	2.86		147
	2.786	301	5.51	2.87		147
	2.786	450	5.60	2.89		147
Granite; Caucasus, USSR	2.70	0.1	3.90	-		138
	2.70	100	5.95	-		138
	2.70	400	6.20	-		138
Granite; Algeria, Africa	2.61	0.1	5.18	3.00	Dry	145
Granite; Westerly, RI	2.63	0.0	4.92	2.94		145
	2.63	10	5.26	3.11		145
Basalt; Pacific Ocean Floor	2.150	20	3.75	1.83	Saturated	141
	2.150	60	3.80	1.89	Saturated	141
	2.150	200	3.89	2.05	Saturated	141
	2.150	600	4.13	2.27	Saturated	141
	2.87	20	6.03	3.28	Saturated	141
	2.87	60	6.09	3.30	Saturated	141
	2.87	200	6.19	3.32	Saturated	141
	2.87	600	6.31	3.35	Saturated	141
Basalt; Atlantic Ocean Floor	2.82	20	5.80	3.11		140
	2.82	60	5.87	3.14		140
	2.82	100	5.90	3.15		140
	2.82	400	6.04	3.21		140
	2.82	1000	6.15	3.29		140

DENSITY AND ELASTIC PROPERTIES (PART C) (Continued)

Rock Type and Location	Density $\rho(g/cm^3)$	Pressure MPa	V_p km/sec	V_s km/sec	Remarks	Ref. No.
Basalt; Monolith, Voronezk, USSR	2.87	0.1	5.53	-		116
	2.87	100	6.04	3.62		116
	2.87	200	6.20	3.66		116
	2.87	600	6.42	3.70		116
	2.87	1000	6.57	3.72		116
Tuff; Kola, Peninsula, USSR	2.83	0.1	5.73	3.26		142
	2.83	50	5.78	3.27		142
	2.83	100	5.82	3.27		142
	2.83	200	5.85	3.30		142
	2.83	500	5.95	3.35		142
Tuff (Ash Flow); Nye Co., NV	1.83	0.1	2.87	1.39	0.85 sat., p = 27	145
	1.83	5	3.20	1.42	0.85 sat., p = 27	145
	1.83	20	3.22	1.48	0.85 sat., p = 27	145
	1.83	60	3.27	1.56	0.85 sat., p = 27	145
	1.83	200	3.43	1.76	0.85 sat., p = 27	145
	1.83	600	3.77	2.10	0.85 sat., p = 27	145
Tuff (Ash Fall), NV	1.98	0.1	3.16	1.69	0.95 sat.	145
	1.80	0.1	2.61	1.51	0.85 sat.	145
	1.97	0.1	2.95	1.25	p = 34, 0.94 sat.	139
	2.01	0.1	3.56	1.84	p = 23, 0.90 sat.	139
	1.88	0.1	2.60	1.17	p = 38, 0.97 sat.	139

DENSITY AND ELASTIC PROPERTIES (PART C) (Continued)

Rock Type and Location	Density $\rho(g/cm^3)$	Pressure MPa	V_p km/sec	V_s km/sec	Remarks	Ref. No.
Tuff (Ash Flow), NV	1.83	0.1	2.87	1.39	p = 27, 0.85 sat.	145
Shale (Green River), UT	2.68	0.1	4.30	2.65	p = 1, dry	144
Shale (Niobrara), WY	2.55	0.1	3.99	2.23	p = 5, dry	144
Shale (Wasatch), UT	2.58	0.1	3.96	2.47	p = 7, dry	144

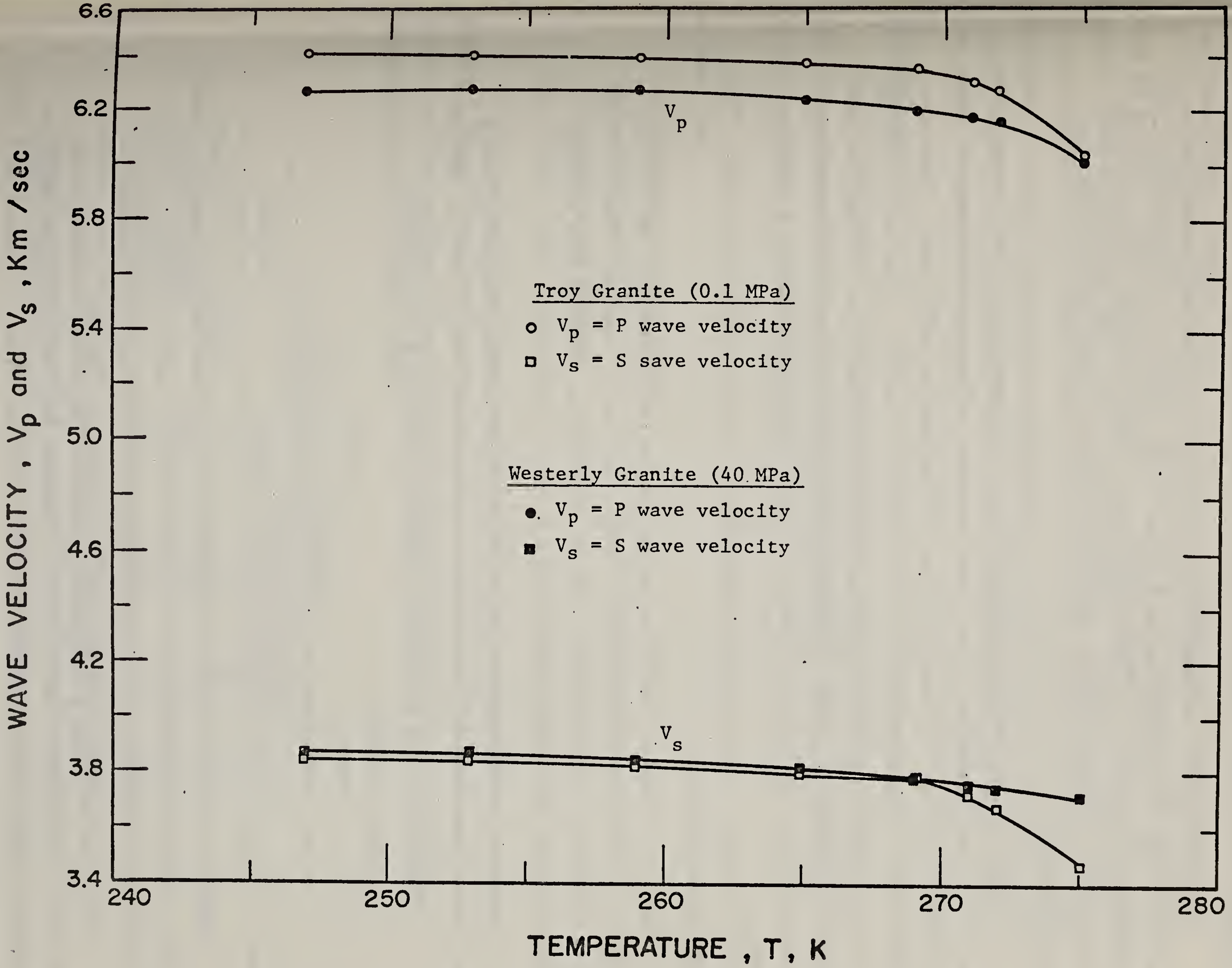

Figure 3. Variation of Wave Velocity with Temperature for Granite [6].

Strength

The true relation between stress and strain for rock undergoing loading can often only be described using a curve. Many factors can affect this relationship and so there is no one unique curve. Some of these factors include temperature, moisture content, confining pressure, stress path loading rate, and strain rate.

In this section the term "strength" has the conventional implication; that is, it is time independent, i.e., time dependent effects are disregarded. Time dependent "strength" is treated in the section dealing with creep. There are three basic strength parameters to be considered; namely: compressive strength $(\sigma_1 - \sigma_3)$, tensile strength $(\sigma_1 - \sigma_3)$, and shear strength (τ). These terms are generally defined for tests of short duration where neither temperatures nor pressures are so extreme as to make the rock behave other than in a brittle fashion.

Compressive Strength

This is defined as the force applied at failure divided by the initial cross sectional area perpendicular to the direction of loading. Usually this is obtained from a uniaxial test, but it can also be obtained from triaxial results though the added sophistication is hardly necessary.

There are several factors which influence the values obtained over and above purely petrological factors such as mineralogy. These factors include:

1) End-effects due to friction between specimen and load platens
2) Specimen geometry
3) Rate of loading
4) Testing environment, e.g., moisture, temperature, etc.

Tensile Strength

Tensile strength of rock is considerably less than the compressive strength. However, since the propagation of tensile cracking leading to tensile failure in rock is not uncommon, it is necessary to assess the tensile strength.

There are basically two methods of determining tensile strength. One is the direct method which implies a direct tensile load on a rock specimen, and the other is the indirect method in which a tensile stress is induced in a specimen rather than directly applied to it.

The direct method is self-explanatory; however, indirect techniques bear some examination. Bending tests and diametral compression of disks give rise to induced tensile stress. In both of these types of test, no direct tensile load is applied. In the case of binding, a certain amount of inaccuracy occurs due to creep which takes place just prior to failure. Disk compression tests (e.g., Brazilian) are somewhat controversial and conflicting results have been reported. Overall it seems some combination of tensile failure and shear failure occurs making the results questionable unless precautions are taken to prevent the feasibility of shear failure.

Shear Strength

Shear strength lacks an exact definition, but here it will be defined as the shearing force necessary to cause failure divided by the cross sectional area along which the failure occurs.

Again, there are several tests for determining shear strength. The basic methods are:

The zero normal stress method
The torsion method
The oblique shear method
The triaxial test

The best agreement and best results are given by the torsion and triaxial methods. Shear tests with compression are considerably better than zero normal stress tests since they do not produce bending, plus the usual tensile stress associated with the latter tests.

TABLE 6.

STRENGTH DATA STATISTICS

Property	No. of Documents			
	Granite	Basalt	Tuff	Shale
Compressive strength	55	15	19	28
Tensile strength	30	7	8	9
Shear strength*	2	0	2	3

*Since there is no unique value for shear strength, the cohesion C and the angle of internal resistance ϕ are given which enables quick assessment of the shear strength over a continuous range of confining pressures.

Discussion of Strength Data

A sample of the tabulated data is presented in the following tables. Data for all four rock types are presented; however, it will be noted that shear strength is poorly represented. This is purely a function of the data available.

The sample curve in Figure 4 was obtained from triaxial compression tests on specially prepared samples of Westerly granite. Normal cylindrical samples have larger diameter steel discs epoxed to each end of the sample with a thick layer of steel reinforced epoxy.

The purpose of this technique was to prevent radial stresses developing at the end of each specimen due to the mismatch in elastic properties between rock and machine platen. This method prevented end effects from extending into the central region of the specimen where failure occurs.

To achieve this, specimens have to be longer and care has to be taken so that binding stresses are not introduced during loading. A feature of this curve is that it is nonlinear, which is what has increasingly come to be expected.

STRENGTH

Shear Strength	τ
Ultimate Strength	σ_{ULT}
Compressive Strength	σ_c
Tensile Strength	σ_t

TABLE 7.

STRENGTH

Rock Type and Location	Shear Strength τ (MPa)		Compressive Strength σ_c (MPa)	Tensile Strength σ_t (MPa)	Remarks	Ref. No.
	C	ϕ				
Granite; Barre, VT			194.4	10.7	Dense, at 50% of failure	93
			112.4-200	-	$p = 2.7$	91
Granite; Ukraine, USSR			294.21	-	$p = 0.72$	40
			269.69	-	$p = 0.66$	40
			253.37	-	$p = 0.72$	40
Gray Granite; North Caucasus, USSR			209.38	-	$p = 0.73$	40
Granite; Valinhos, Quarry, Brazil			100.0	-	$p = 1.3$	108
Granite; Cantarcira, Quarry, Brazil			121.0	-	$p = 0.9$	108
Granite; Unaweep, CO			175.8	4.1	$p = 0.5$	45
			158.6	3.6		45
			161.3	5.6	$p = 0.6$	45
			174.4	3.4	$p = 0.6$	45
Granite; Harcourt, Vic., Australia			143.9	-		37
Basalt; Black Canyon Dam, ID			57.9	3.17		48
Basalt; South Coulee Dam, WA			171.7	-		48
			95.8	-	Vesicular	48
			82.1	-		48
			61.4	-	Vesicular	48
Dresser Basalt, USA			292.3	-		86
Basalt; Jupia Dam, Brazil			104.8	-		108

STRENGTH (Continued)

Rock Type and Location	Shear Strength (MPa)		Compressive Strength σ_c (MPa)	Tensile Strength σ_t (MPa)	Remarks	Ref. No.
	C	ϕ				
Basalt; Barra Bonita Dam, Brazil			137.4	-		108
Basalt; Jurumirim Dam, Brazil			133.0	-		108
Basalt; Mussa Quarry, Brazil			126.8	-		108
Basalt; AEC, Nevada test site			148.0	18.0	At 50% of failure	120
Basalt; Medford, OR			169.8	-	p = 0-41.6	129
Basalt, MI			232.0	-	Altered	129
			81.9	-	Altered	129
			120.0	14.6	Altered, amygdaloidal	129
Tuff; Kirkland, Ont., Canada			289.58	-	p = 1.5	128
Tuff			35.3	-	Yellow, w = 17.5	56
			22.3	-	Red and yellow, w = 4.6	56
Tuff; NTS-E Tunnel, USA			24.1	1.45		93
Tuff; Lakeshore, Canada			262.92	105.49		96
Tuff; Helen Mine, Canada			155.13	17.31	Vertical	96
Lithic Tuff; Medowell Dam, AZ			15.86	-	Altered	48
Tuff; Green Peters Dam, USA	7.0	24	23.0	-		57
	7.7	19	22.0	-		57

STRENGTH (Continued)

Rock Type and Location	Shear Strength (MPa)		Compressive Strength σ_c (MPa)	Tensile Strength σ_t (MPa)	Remarks	Ref. No.
	C	ϕ				
Tuff; AEC Nevada test site			11.3	1.17		121
Tuff; Seikan Tunnel, Japan			21.9	2.2		95
Rochester Shale; Niagara, NY			-	-		70
Shale; Niagara, NY			110.32	-		70
Oil Shale; Rifle, CO			-	17.0		111
Shale; USBM site 9, Rock Springs, WY			-	23.0		111
Shale; Bearpaw, Sask River Dam, Canada			0.06-0.63	-	w = 32	106
			1.2-3.2	-	w = 23	106
Shale; USA			43.1	-		3
			48.3	-		34
Shale; Estancia Valley, USA			59.3	-		49
			72.4	-		49
Shale; Seikan Tunnel, Japan			62.9	10.7		95
Shale; Brunswick, NJ			1.63-7.52	-		78

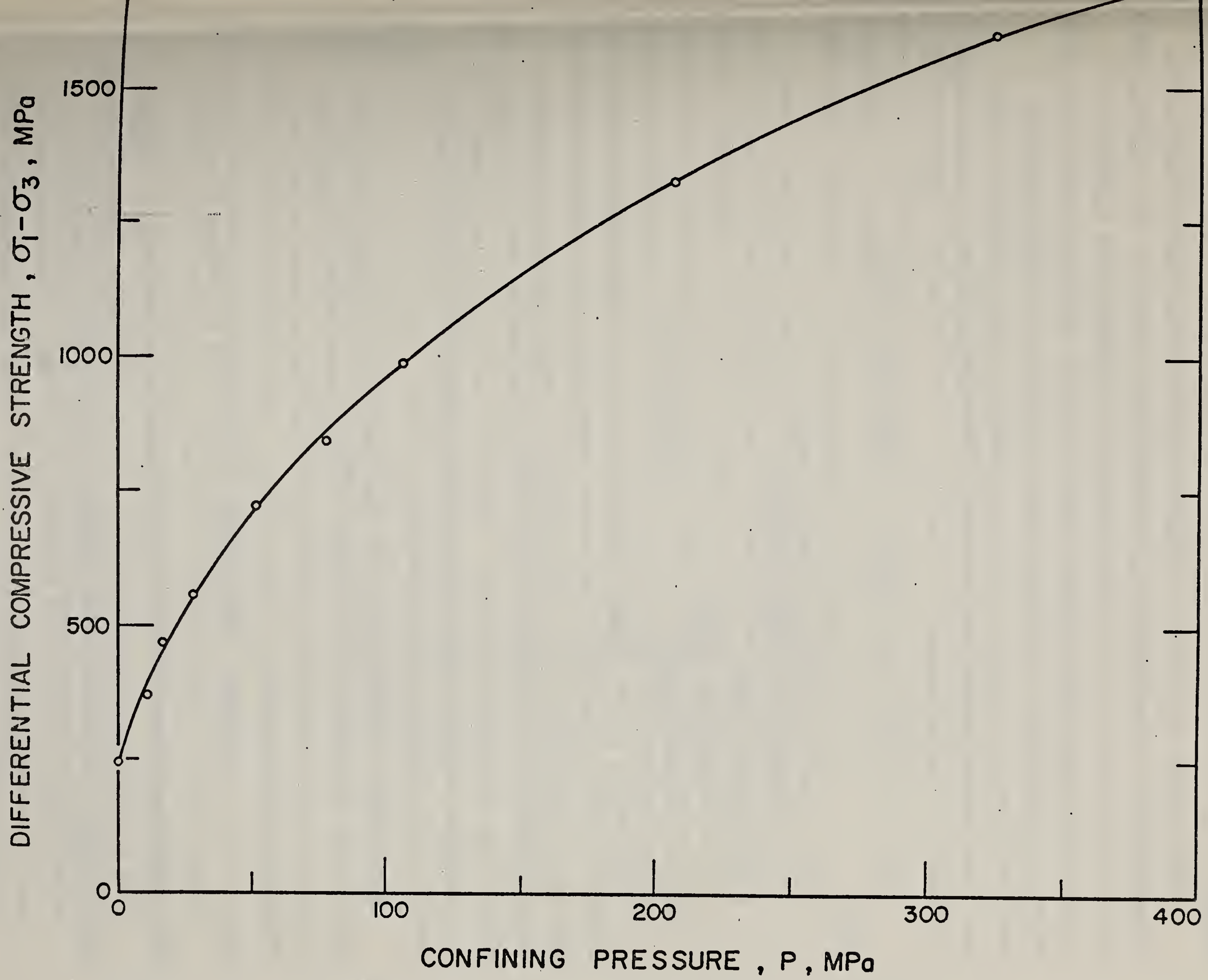

Figure 4. Relation Between Compressive Strength and Confining Pressure in Westerly Granite [13].

Creep

Three general approaches are usually adopted to study creep. They are the micromechanistic, phenomonological, and empirical methods. Of the three, the latter is the most popular. In this technique, experiments are conducted to obtain a continuous stress-strain history in terms of parameters like time, stress, and temperature. This information is then used to derive empirical creep equations that describe a particular material's creep behavior. A general equation which defines the performance of a material over its entire range of behavior is the following:

$$\varepsilon(t) = \varepsilon_0 + \varepsilon_p(t) + A(t) + \varepsilon_T(t) \qquad \text{(Emery et al. [41])}$$

where

$\varepsilon(t)$ = total strain (i.e., elastic + creep)
ε_0 = instantaneous strain (elastic)
$\varepsilon_p(t)$ = primary creep
$A(t)$ = steady state creep
$\varepsilon_T(t)$ = tertiary creep (See Figure 5)

Since rock is not an ideally elastic material, its behavior is usually complex and often a function of the mineral composition. This complexity gives rise to the problem that it is often difficult to characterize a rock quantitatively without first obtaining stress-strain relationships over the entire range of the conditions anticipated. Theoretical modeling of the stress-strain or time-strain behavior is greatly hindered by the variations in environment possible, e.g., temperature, pressure, etc.

Definitions of characteristics of time-dependent properties are far from universal and controversy still exists. For this reason nomenclature will be defined here and hereafter all references to a particular characteristic will assume these definitions.

Creep: plastic deformation under constant load showing an obvious decreasing strain rate.

Yield Point: some materials show a sudden inhomogeneous extension at constant load in their stress-strain curves as soon as the elastic limit is exceeded.

Yield Strength: to circumvent the problems associated with determining the elastic limit accurately for materials not showing a yield point, one normally chooses an arbitrary plastic strain, usually 0.2%, and quotes the related stress as the yield strength.

Plasticity: behavior of a solid material once the elastic limit has been exceeded and implies permanent non-recoverable strain.

Creep Strength: the stress in a constant stress, constant temperature test that will produce a specified strain in a specified time.

Plastic Creep Limit: implies below a certain stress all creep is anelastic (= fully recoverable with time once load is removed), whilst above it creep is partly anelastic and partly plastic.

Anelastic Creep: creep fully recoverable with time once load is removed.

Ultimate Strength: the maximum stress immediately prior to failure.

Creep Stress: conventional stress in a creep test.

Creep Strain: the gradual strain observed in creep.

Creep Rate: the slope of the stress-strain curve in the creep stage.

Creep is determined from so-called creep tests which are constant stress tests. These tests can be accomplished in several modes; namely: in bending, torsion, compression, or tension. Two approaches are used in these tests. One is to load the specimen and subject it to this load for a long period while measuring deformation with time. The other is to load the specimen incrementally and measure the deformation with time for each increment. In all these cases, steady state creep is what is required.

An idealized curve for rock at constant stress is shown in the figure on the following page.

Primary (transient) and secondary (steady state) creep represent the bulk of the creep work done on rock. Generally, empirical equations have been developed by researchers to fit the time-strain behavior recorded by their experiments. Numerical methods have more recently been used to achieve fits for experimental data.

Several factors influence creep. At this stage it is not our intent to delve into them in any detail other than just to mention them. They are:

1) Nature of the stress, i.e., tensional or compressional, etc.
2) Level of stress (relationship between creep-stress is not necessarily linear.
3) Confining pressure (increase in confining pressure decreases creep rate).
4) Temperature (generally an increase in temperature causes an increase in creep rate.
5) Moisture and humidity (creep seems to increase with wetting).
6) Structural effects (variation in grain size, crystal orientation produce effects).

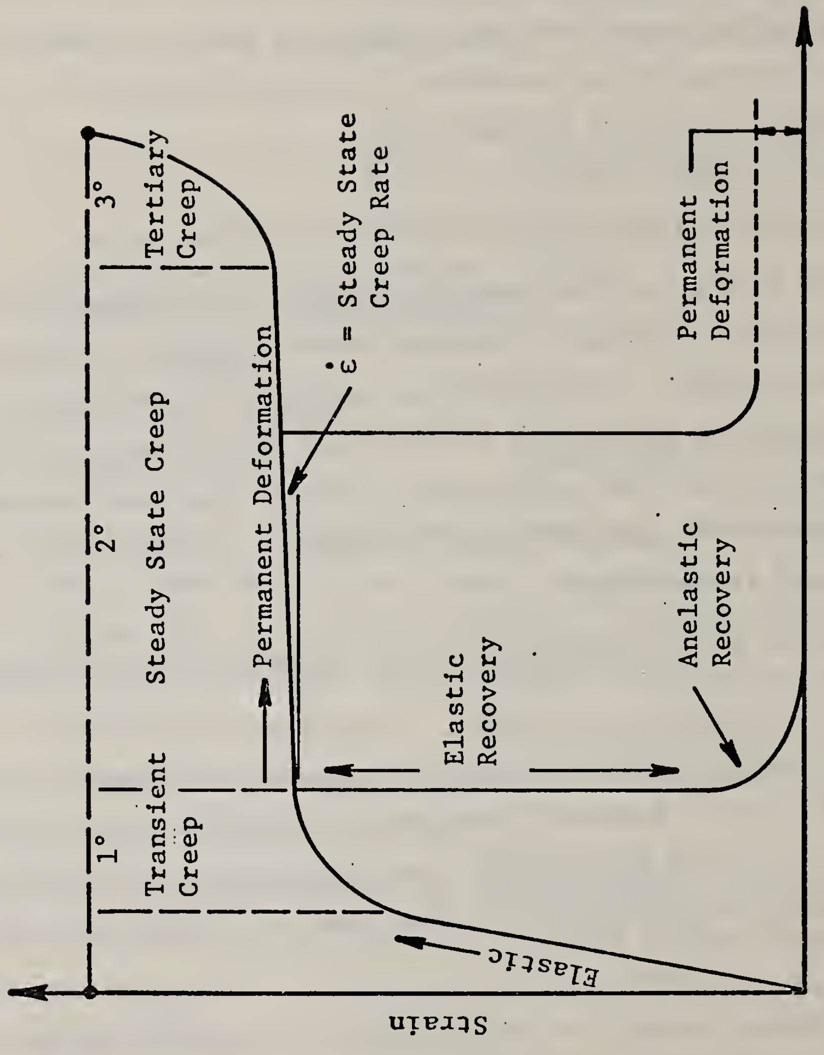

Figure 5. Ideal Creep Curve.

Creep of Rock In-Situ

Most research has been accomplished on rock salt. Several creep relationships have been developed, generally for underground openings or pillars in rock salt mines. The diversity of relationships developed tends to lead to the conclusion that, as has been indicated earlier, the mechanism of creep is not at all well characterized and so it would seem prototype modeling in the in-situ case is still the best way to go if creep parameters are required.

Time Dependent "Strength"

This, arguably, could be presented under the section entitled "Strength." However, as it will be seen later, strength will be defined as time independent for the purposes of this report, although there is a grey area where time effects overlap. For this reason it is probably better to present data as stress-strain or time-strain data and allow the user to select so-called "strength" values for his particular purpose. Obviously, neither of these two forms are totally independent of time in the former instance and stress in the latter instance, but at least these two parameters have been "de-emphasized" to some extent due to the nature of the testing being used.

Using the terminology of Price [71], this section deals with "long term strength." This "strength" can be assessed using either direct or indirect methods. The direct method is iterative in nature and is essentially a "trial and error" method. It required that several creep tests be done at differing loads and the highest load at which no failure takes place enables an assessment of the "long term strength." This method is conservative and generally only approximate.

TABLE 8.

CREEP DATA STATISTICS

Rock Type	No. of Documents
Granite	4
Basalt	0
Tuff	0
Shale	2

Discussion of Creep Data

It will be noted that no tabular data are presented because the literature presents such data as either curves or equations derived from those curves.

A sample of such time dependent deformation data is produced in Figure 6. Specimens for the test were cored from a block of Westerly granite. Confining pressures of up to 1 GPa were achieved using an argon pumping system.

Creep readings were measured up to the melting point of the granite (993 K) under confining pressures of 400 to 500 MPa and water pressures of 100 MPa.

A series of runs at different temperatures, but at a single load of 64 MPa, are plotted against the log of time in Figure 6. In this figure anelastic strain has been normalized against the initial elastic strain. As is expected, creep is greater at higher temperatures.

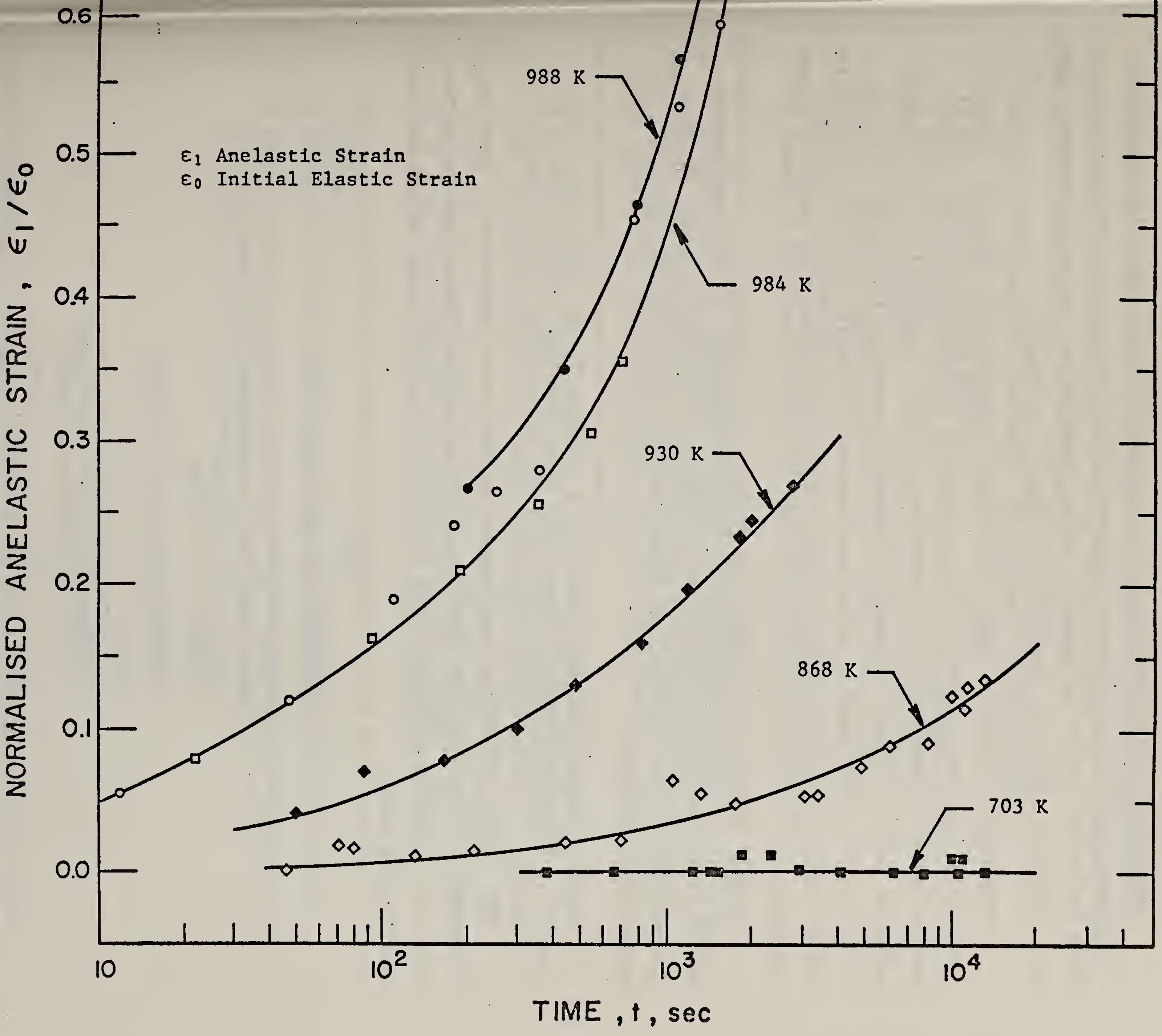

Figure 6. Normalized Anelastic Creep Curves of Westerly Granite at Various Temperatures for a Stress of 64 MPa [32]

Permeability

Permeability is a function of the porosity of rock. Fluid is transmitted throughout a rock by interconnecting pores. The fact that a rock is porous does not imply that it is permeable since closed pores (not interconnected with the external surface) do not allow the passage of fluids.

Permeability can be a highly anisotropic property; for instance, radial permeability may vary greatly from longitudinal permeability within a rock. Another point to consider is the permeating medium. Permeability is obviously going to vary with fluid viscosity. Generally speaking, laboratory tests are of two basic kinds; namely, either gas permeability tests or liquid permeability tests. Each of these, in turn, can usually be broken down into radial or longitudinal tests.

In-situ tests are generally much better indications of rock mass permeability since they take into account the effects of fractures within the mass. Two conditions exist in-situ, one being the fully saturated case and the other the unsaturated case.

Water is pumped from the ground via a borehole in the former case. The reverse is true in the latter since water has to be pumped into the ground.

More recent methods use radioactive isotope tracer techniques. These are introduced into water at one location and their arrival time at another point is noted. Isotopes with very short half lives are chosen so as not to contaminate ground water.

TABLE 9.

PERMEABILITY DATA STATISTICS

Rock Type	No. of Documents
Granite	4
Basalt	2
Tuff	4
Shale	2

Data for both permeability and the following porosity are presented together since permeability is a function of porosity in many cases. Only tabular data are presented.

Porosity

Porosity is defined as the ratio of the volume of internal open spaces (pores or voids) to the bulk volume of the rock. It can also be expressed in terms of grain density and the dry density of the rock.

Factors which generally influence the porosity of rocks are:

1) Size distribution of grains
2) Shape of grains
3) Solidity of grains
4) Orientation of grains
5) Degree of compaction
6) Amount of nongranular material in pores or coating of grains

Pores are either interconnected and open to the exterior or closed (isolated) and not connected to the exterior. Different terminology applies to these two cases. When only interconnected open pores are considered, the porosity is known as apparent porosity. When both open and closed pores are considered, the value obtained is termed total porosity.

If at least two of the three forms of volumes (for example, grain volume, pore volume, and bulk volume) are known, one can calculate porosity. Methods of obtaining these volumes are cited in several sources and will not be discussed here. Porosity has the effect on the mechanical properties of rocks that all strength properties decrease with increase in porosity because:

1) Stress concentration caused on the boundary of the pores reduces the strength.
2) Decrease in the bearing area of the rock causes decrease in strength.
3) Pores may be filled with water or some other liquid which may help in crack propagation by reaction at the points of stress concentration by reducing its surface energy.

TABLE 10.

POROSITY DATA STATISTICS

Rock Type	No. of Documents
Granite	29
Basalt	10
Tuff	18
Shale	13

PERMEABILITY AND POROSITY

Permeability	k
Porosity	p

TABLE 11.

PERMEABILITY AND POROSITY

Rock Type and Location	Permeability cm/sec	Porosity %	Fluid	Loading Conditions	Temp. K	Remarks	Ref. No.
Shale; Lower Pliocene, Italy	4.4×10^{-10}	11.8	-	-	-		169
Shale; Middle Miocene, Italy	2.6×10^{-9}	16.6	-	-	-		169
Shale	3.9×10^{-9}	-	-	-	-	Cretaceous	161
Shale; Lower Pliocene, Italy	3.9×10^{-9}	10.3	-	-	-		169
	4.8×10^{-8}	23.0	-	-	-		169
Shale; Lower Pliocene, Italy	9.7×10^{-12}	5.9	-	-	-		169
Shale; Pennsylvania	8.7×10^{-11}	-	-	-	-		161
Shale; Lower Pliocene, Italy	1.4×10^{-10}	12.0	-	-	-		169
Shale; Upper Triassic, Italy	1.6×10^{-10}	12.5	-	-	-		169
Shale; Lower Pliocene, Italy	2.2×10^{-10}	13.3	-	-	-		169
Tuff; Nevada Test Site	2.8×10^{-9}	11.0	Water	-	-	Clayey	180
	3.9×10^{-8}	38.8	Water	-	-	Bedded	164
	3.2×10^{-7}	14.1	Water	-	-	Wleded	164
	6.4×10^{-7}	14.1	Air	-	-	Welded	164
	8.7×10^{-7}	38.8	Air	-	-	Bedded	164
	1.3×10^{-6}	35.5	Water	-	-	Friable	164
	2.4×10^{-6}	37.7	Water	-	-	Zeolitized	180
	5.8×10^{-6}	35.5	Air	-	-	Friable	164
	1.1×10^{-5}	40.2	Water	-	-	Pumiceous, bedded	164
	2.0×10^{-5}	40.2	Air	-	-	Pumiceous, bedded	164

PERMEABILITY AND POROSITY (Continued)

Rock Type and Location	Permeability cm/sec	Porosity %	Fluid	Loading Conditions	Temp. K	Remarks	Ref. No.
Tuff	1.9×10^{-4}	41	Water	-	288.5	Vertical	168
	2.4×10^{-4}	41	Water	-	288.5	Horizontal	168
Tuff, Nevada	-	38.8	-	-	-	Bedded	164
Tuff	-	40.2	-	-	-	Bedded, pumiceous	164
	-	41.0	-	-	-		168
Sherman Granite	-	0.002	-	-	-	Effective flow porosity	173
Granite; Barre, VT	-	0.079	-	-	-		167
Granite; Westerly, RI	-	0.106	-	-	-		167
Granite; Stone Mt., GA	-	0.3	-	-	-		149
Granite	-	0.4	-	-	-		160
	-	0.7	-	-	-		167
	-	0.9	-	-	-		163
Granite	9.5×10^{-10}	-	Water	Variable	297		172
	7.5×10^{-9}	-	Water	Variable	297		172
Granite; Barriefield, Ontario	4.9×10^{-11}	-	-	-	-		171
Sherman Granite; Laramie, WY	1.0×10^{-9}	-	-	-	-		173
Granite; Quincy, MA	4.4×10^{-9}	-	-	-	-		171
Granite	1.6×10^{-3}	45.0	Water	-	288.5	Weathered	168
Basalt; Jurimirim Dam, Brazil	-	4.2	-	-	-		108
Basalt; Mussa Quarry, Brazil	-	5.7	-	-	-		108

PERMEABILITY AND POROSITY (Continued)

Rock Type and Location	Permeability cm/sec	Porosity %	Fluid	Loading Conditions	Temp. K	Remarks	Ref. No.
Basalt; Melhurb Quarry, Brazil	-	11.6	-	-	-		108
Basalt; Armenia, USSR	-	5.0	-	-	-	Dry	137
	-	4.0	-	-	-	Dry	137
	-	6.0	-	-	-	Dry	137
Andresite-Basalt; Bakuriani Georgia, USSR	-	21.86	-	-	-		39
Basalt; Jupia Dam, Brazil	-	2.1	-	-	-	Compact	108
Basalt; Barra Bonita Dam, Brazil	-	1.4	-	-	-	Compact	108

Discussion of Hardness Data

Several measures of hardness exist, many of them being developed for metallurgical purposes. Certain scales have been utilized to describe the hardness of rock. The most famous of these is the Mohr's scale; however Vickers microhardness and Shore scleroscopic hardness are also commonly used. Some difficulty has been encountered in isolating hardness data for some of the rock types. This is probably due to the character of the rock, e.g., friability, which makes testing difficult.

TABLE 12.

HARDNESS DATA STATISTICS

Rock Type	No. of Documents
Granite	2
Basalt	1
Tuff	0
Shale	0

HARDNESS

Mohs Hardness
Vickers Hardness
Shore Hardness

CONCLUSION

This report is a summary of the various properties investigated and also an indication of the state of the art, both with respect to the amount of data available and the testing techniques existent. Additionally, partial data for all four rock types have been provided.

In certain cases data are sparse and this is largely a function of either lack of published data or difficulty in isolating and retrieving data which is either unpublished or obscure. In data collection of this type, heavy dependence is placed on existing abstracting and indexing services available nationally and internationally. Unfortunately, experience often indicates that these services are not quite as complete as they might seem and so it is possible to miss valuable contributions. In the present work, all reasonable attempts have been made to obtain as much salient data as possible. An added difficulty is that research on certain rock types may still be fairly rare and so, in actuality, there is very little in the way of data available.

TABLE 13.

HARDNESS

Rock Type and Location	Hardness Mohs (2)	Hardness Avg. Vickers kg/mm^3 (3)	Hardness Shore (4)	Remarks	Ref. No.
Granite; Inada, India	6.1	860	-		17
Granite; Mannari, India	6.5	860	-		17
Granite; Barre, VT	6.1	860	-		17
Granite; Stone Mt., GA	6.3	860	-		17
Granite; Westerly, RI	6.3	860	-		17
Barre Granite	-	-	90.3		23
	-	-	87.3		23
	-	-	88.8		23
Westerly Granite	-	-	93.8		23
	-	-	92.4		23
	-	-	94.2		23
Dresser Basalt	-	-	95.0		23
	-	-	93.2		23
	-	-	94.2		23

Properties which at present have limited data will be supplemented wherever possible through personal contacts with specialists in the field. Presentation of the final report will be in the same format as the present report in that it will contain some figures and a large number of data tables in addition to a complete bibliography.

BIBLIOGRAPHY

1. Haimson, B.C., "Engineering Geology, Stress Regime and Mechanical Properties of Some Precambrian Rocks in South Central Wisconsin," Wisconsin Geological Survey Information Circular.

2. Lindholm, U.S., Yeakley, L.M., Nagy, A., "The Dynamic Strength and Fracture Properties of Dresser Basalt," Int. J. Rock Mech. & Min. Sci. & Geomech. Abstr., 11, 181-91, 1974.

3. Birch, F., "The Velocity of Compressional Waves in Rocks to 10 Kilobars," J. Geophys. Res., 65, 1960.

4. Nur, A. and Simmons, G., "The Effect of Viscosity of a Fluid Phase on Velocity in Low-Porosity Rocks," Earth Planet. Sci. Lett., 7(99), 1969A.

5. Nur, A. and Simmons, G., "The Effect of Saturation on Velocity in Low Porosity Rocks," Earth Planet. Sci. Lett., 7(183), 1969B.

6. Takeuchi, S. and Simmons, G., "Elasticity of Water-Saturated Rocks as a Function of Temperature and Pressure," J. Geophys. Res., 78(17), 1973.

7. Kumar, A., "The Effect of Stress Rate and Temperature on the Strength of Basalt and Granite," Geophysics, 33(3), 1968.

8. Norman, C.E., "Behaviour of Brittle Rock in Multi Increment Creep Tests," Geol. Soc. Amer., Eng. Geol. Case Histories Number 11, 17-23, 1977.

9. Cogan, J., "Triaxial Creep Tests on Opohonga Limestone and Ophir Shale," Int. J. Rock Mech. Min. Sci., 13(1), 1-10, 1976.

10. Stephens, D.R., Heard, H.C., and Schock, R.N., "High Pressure Mechanical Properties of Tuff from the Diamond Dust Site," Lawrence Radiation Lab. Rept. UCRL 50858, 14 pp., 1970.

11. Podio, A.L., Gregory, A.R., and Gray, K.E., "Dynamic Properties of Dry and Water-Saturated Green River Shale Under Stress," Soc. Pet. Eng. J., 8(4), 389-404, 1968.

12. Jerome, S.E., "Geological, Geophysical, Chemical and Hydrological Investigations of the Sand Springs Range, Fairview Valley, and Fourmile Flat, Churchill County, Nevada," U.S. Atomic Energy Rept. VUS-1001, 369 pp., 1964.

13. Mogi, K., "Some Precise Measurements of Fracture Strength of Rocks Under Uniform Compressive Stress," Felsmech. Ingenieurgeol., 4, 41-55, 1966.

14. Zoback, M.D. and Byerlee, J.D., "The Effect of Cyche Differential Stress on Dilatancy in Westerley Granite Under Uniaxial and Traxial Conditions," J. Geophys. Res., 80, 1521-30, 1975.

15. Peng, S. and Podnieks, E.R., "Relaxation and the Behaviour of Failed Rock," Int. J. Rock. Mech. Min. Sci., 9, 699-712, 1972.

16. Hoskins, J.R. and Horino, F.G., "Influence of Spherical Head Size and Specimen Diameters on the Uniaxial Compressive Strength of Rocks," Bureau of Mines Rept. RI-7234, 1969.

17. Ohnaka, M., "The Quantitative Effect of Hydrostatic Confining Pressure on Strength of Rock," J. Phys. Earth, 21(2), 125-40, 1973.

18. Stephens, D.R., "Hydrostatic Compression of Eight Rocks," J. Geophys. Res., 69, 2967, 1964.

19. Hooke, V.E., Bickel, D.L., and Aggson, J.R., "In-Situ Determination of Stresses in Mountainous Topography," Bureau of Mines Rept. RI-7654, 24 pp., 1972.

20. Sundae, L.S., "Effect of Specimen Volume on Apparent Tensile Strength of Three Igneous Rocks," Bureau of Mines Rept. RI-7846, 31 pp., 1974.

21. Fayed, L.A., "Shear Strength of Some Argillaceous Rock," Int. J. Rock Mech. Min. Sci., 5, 79-85, 1968.

22. Yamaguchi, U., "The Number of Test-Pieces Required to Determine the Strength of Rock," Int. J. Rock Mech. Min. Sci., 7, 209-27, 1970.

23. Krech, W.W., Henderson, F.A., and Hjelmstad, K.E., "A Standard Rock Suite for Rapid Excavation Research," Bureau of Mines Rept. BM-RI-7865, 29 pp., 1974.

24. Simvasan, P.B., "Engineering Properties of Foundation Rocks at Koyna Dam," J. Eng. Geol., 6, 325-30, 1971.

25. Mogi, K., "Effect of Intermediate Principal Stress on Rock Failure," J. Geophys. Res., 72, 5117-31, 1967.

26. Christensen, N.I., "Compressional and Shear Wave Velocities in Basaltic Rocks, Deep Sea Drilling Project, Leg 16," Initial Rept. Deep Sea Drill. Proj., 16, U.S. Government Printing Office, 647-9, 1973.

27. Christensen, N.I., "Compressional and Shear Wave Velocities in Elastic Moduli of Basalts, Deep Sea Drilling Project, Leg 19," Initial Rept. Deep Sea Drill. Proj., 19, U.S. Government Printing Office, 657-9, 1973.

28. Hyndman, R.D., "Seismic Velocities of Basalts from DSDP Leg 26," Initial Rept. Deep Sea Drill. Proj., 26, U.S. Government Printing Office, 509-11, 1974.

29. Salisbury, M.H. and Christensen, N.I., "Sonic Velocities and Densities of Basalts from Nazca Plate, DSDP Leg 34," Initial Rept. Deep Sea Drill. Proj., 34, U.S. Government Printing Office, 543-6, 1976.

30. Christensen, N.I., "Seismic Velocities, Densities, and Elastic Constants of Basalts from DSDP Leg 35," Initial Rept. Deep Sea Drill. Proj., 35, U.S. Government Printing Office, 335-7, 1976.

31. Carlson, R.L. and Christensen, N.I., "Velocities, Densities, and Elastic Constants of Basalt and Trachytic Tuff, DSDP Leg 39," Initial Rept. Deep Sea Drill. Proj., 39, U.S. Government Printing Office, 493-6, 1977.

32. Goetze, C., "High Temperature Rheology of Westerly Granite," J. Geophys. Res., 76(5), 1223-30, 1970.

33. Adams, F.D. and Coker, E.G., "An Investigation into the Elastic Constants of Rocks, Especially with Reference to Cubic Compressibility," Carnegie Institute, Washington, Pub. No. 46, 69 pp., 1906.

34. Avedissian, Y.M. and Wood, L.E., "Prediction of Compressive Strength of Rock from Its Sonic Properties," Proc. 10th Symp. Rock Mech., Univ. of Texas, Austin, Texas, 55-71, 1968.

35. Avila, F.P., "Some Applications of Seismic Field Tests in Rock Media," Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, Vol. I, 3-6, 1966.

36. Balmer, G.G., "Physical Properties of Some Typical Foundation Rocks," U.S. Bureau of Reclamation, Concrete Lab. Rept. SP-59, 150 pp., 1953.

37. Bamford, W.E., "Anisotropy and Natural Variability of Rock Properties," Proc. Symp. Rock Mech., Univ. Sydney, 1-10, 1969.

38. Bauer, A. and Calder, P.N., "Open Pit Drilling Factors Influencing Drilling Rates," Proc. 4th Can. Rock Mech. Symp., Ottawa, 1-33, 1967.

39. Belikov, B.P., "Plastic Constants of Rock-Forming Minerals and Their Effect on the Elasticity of Rocks," in Physical and Mechanical Properties of Rocks (Zalesskii, B.V., Editor), Jerusalem, Israel Program for Scientific Translations, 124-40, 1967.

40. Belikov, B.P., Zalesskii, B.V., Rozanov, Y.A., Sanina, E.A., and Timchenko, I.P., "Methods of Studying the Physico-Mechanical Properties of Rocks," in Physical and Mechanical Properties of Rocks (Zalesskii, B.V., Editor), Jerusalem, Israel Program for Scientific Translations, 1-58, 1967.

41. Emery, J.J., Hanafy, E.A., and Franklin, J.A., "Creep Movements Associated With Excavations in Rock," Conference on Large Ground Movement and Structures, Institution of Structural Engineers, Cardiff, 26 pp., 1977.

42. Birch, F. and Bancroft, D., "Elasticity and Internal Friction in a Long Column of Granite," Bull. Seismol. Soc. Am., 28, 243-54, 1938.

43. Birch, F. and Bancroft, D., "The Elasticity of Certain Rocks and Minerals," Am. J. Sci., 237, 2-66, 1939.

44. Blair, B.E., "Physical Properties of Mine Rock, Part III," Bureau of Mines Rept. RI-5130, 69 pp., 1955.

45. Blair, B.E., "Physical Properties of Mine Rock, Part IV," Bureau of Mines Rept. RI-5244, 69 pp., 1956.

46. Borecki, M. and Chudek, M., Mechanika Gorotworu., "Slack," Katowice, 1972.

47. Brace, W.F., "Brittle Fracture of Rocks," Proc. Int. Conf. State of Stress in the Earth's Crust, Santa Monica, California, 110-74, 1963.

48. Brandon, T.R., "Rock Mechanics Properties of Typical Foundation Rock Types," U.S. Bureau of Reclamation Rept. REC-ERC. 74-10, Denver, Colorado, 1974.

49. Bratton, J.L. and Pratt, H.R., "Two Dimensional Finite Difference Calculations of Dynamic InSitu Response of Layered Geologic Media to a Large Explosive Load," Proc. 10th Symp. Rock Mech., Univ. of Texas, Austin, Texas, 149-98, 1968.

50. Breyer-Kassel, H., "Uber die Elastizitat von Gesteinen," Zeitschr. Geophysik, 6, 98-111, 1930.

51. Brown, E.L., Charlambakis, S., Crepeau, P.M., and Le Francois, P., "Les Foundations du Barrage Daniel-Johnson (Manicougan 5)," Trans. 10th Cong. Large Dams, Montreal, Vol. II, 631-50, 1970.

52. Clark, S.P. (Editor), Handbook of Physical Constants, Geol. Soc. Am. Mem., 97, 1966.

53. Clark, G.B. and Caudle, R.D., "Failure of Homogeneous Rock Under Dynamic Compressive Loading," Proc. Int. Conf. State of Stress in the Earth's Crust, Santa Monica, California, 300-20, 1963.

54. Clark, G.B., Rollins, R.R., Brown, J.W., and Kalia, H.N., "Rock Penetration by Jets from Lined Cavity Explosive Charges," Proc. 12th Symp. Rock Mech., Rolla, Missouri, 621-51, 1970.

55. Coates, D.F. and Parsons, R.C., "Experimental Criteria for Classification of Rock Substances," Int. J. Rock Mech. Min. Sci., 3, 181-9, 1966.

56. Cording, E.J., "The Stability During Construction of Three Large Underground Openings in Rock," Univ. of Illinois, Ph.D. Thesis, 1967.

57. Corns, C.F. and Nesbitt, R.H., "Sliding Stability of Three Dams on Weak Rock Foundations," Trans. 9th Cong. Large Dams, Istanbul, I, 463-86, 1967.

58. Creuels, F.H. and Hermes, J.M., "Measurement of the Changes in Rock Pressure in the Vicinity of a Working Face," Proc. Int. Strata Control Cong., Essen., 1956.

59. Denkhaus, H.G., "Strength of Rock Material and Rock System," Int. J. Rock Mech. Min. Sci., 2, 111-26, 1965.

60. Wei-Ch'ing, F., "Dynamic Pulse Method of Determining Elastic Parameters of Rock Samples Under High All-Sided Pressures," Bull. (Izv.) Acad. Sci., USSR Geophys. Ser., 10, 1004-8, 1961.

61. Fumaglli, E., "Stability of Arch Dam Rock Abutments," Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, Vol. II, 503-8, 1966.

62. Gassmann, Weber and Vogtli., Verh. Schweiz. Naturforsch. Ges., Bern., 1952.

63. Geyer, R.L. and Myung, J.I., "The 3-D Velocity Log: A Tool for Insitu Determination of the Elastic Moduli of Rocks," Proc. 12th Symp. Rock Mech., Rolla, Missouri, 71-107, 1970.

64. Haimson, B.C. and Fairhurst, C., "Insitu Stress Determination of Great Depth by Means of Hydraulic Fracturing," Proc. 11th Symp. Rock Mech., Berkeley, California, 559-84, 1969.

65. Hardy, H.R., "Standardized Procedures for the Determination of the Physical Properties of Mine Rock Under Short-Period Uniaxial Compression," Dept. Mines & Tech. Surveys, Mines Branch, Canada, TB-8, Dec. 1959.

66. Hartman, H.L., "The Effectiveness of Indexing in Percussion and Rotary Drilling," Int. J. Rock Mech. Min. Sci., 3, 265-78, 1966.

67. Hawkes, I., Mellor, M., and Gariepy, S., "Deformation of Rocks Under Uniaxial Tension," Int. J. Rock Mech. & Min. Sci. & Geomech. Abstr., 10, 493-507, 1973.

68. Herget, G., "Variation of Rock Stresses with Depth at a Canadian Iron Mine," Int. J. Rock Mech. Min. Sci., 10, 37-51, 1973.

69. Hobbs, D.W., "Stress-Strain-Time Behaviour of a Number of Coal Measure Rocks," Int. J. Rock Mech. Min. Sci., 7, 149-70, 1970.

70. Hogg, A.D., "Some Engineering Studies of Rock Movement in the Niagara Area," in Engineering Geology Case Histories (Trask, P. and Kiersch, G.A., Editors), Geol. Soc. Am., Numbers 1-5, 1964.

71. Price, N.J., Fault and Joint Development in Brittle and Semi-Brittle Rock, Pergamon Press, Oxford, England, 1966.

72. Huck, P.J. and Singh, M.M., "Effect of Specimen Size on Confined Compression Testing of Rock Cores," IIT Research Centre, Project No. D6059, 1972.

73. Ide, J.M., "Comparison of Statically and Dynamically Determined Young's Modulus of Rocks," Proc. Nat. Acad. Sci. USA, 22, 81-92, 1936.

74. Ide, J.M., "The Elastic Properties of Rocks. A Correlation of Theory and Experiment," Data. Proc. Nat. Acad. Sci. USA, 22, 482-596, 1936.

75. Iida, K., Wada, T., Iida, Y., and Shichi, R., "Measurements of Creep in Igneous Rocks," J. Earth Sci., Nagoya Univ., 8(1), 1-16, 1960.

76. Imrie, A.S. and Jory, L.T., "Behaviour of the Underground Power House Arch at the WAC Bennett Dam During Excavation," Proc. 5th Can. Rock Mech. Symp., Toronto, 203 pp., 1969.

77. Judd, W.R., "Statistical Methods to Compile and Correlate Rock Properties," School of Civil Engineering, Purdue Univ., W. Lafayette, Indiana, 109 pp., 1969.

78. Jumikis, A.R., "Some Engineering Aspects of Brunswick Shale," Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, 1, 99-102, 1966.

79. Kitahara, Y., Fujiwara, Y., and Kawamura, M., "The Stability of Slope During Excavation - The Method of Analysis and Observation," Rock Mech. in Japan, Vol. II, 187-9, 1974.

80. Kluth, D.J., "Rock Stress Measurements in the Jor Underground Power Station of the Cameroun Highlands Hydro-Electric Scheme," Malaya. Trans. 8th Cong. Large Dams, Edinburgh, Vol. I, 103-19, 1964.

81. Knopoff, L., "Seismic Wave Velocities in Westerly Granite," Trans. Am. Geophys. Union, 35, 969-73, 1954.

82. Koifman, M.I., "Quick Combined Method of Determining Mechanical Properties of Rocks," in Mechanical Properties of Rocks, Jerusalem, Israel Program for Scientific Translations, 74-86, 1969.

83. Koifman, M.I. and Chirkov, S.E., "Prophilographic Investigations and Correct Data on Mechanical Properties of Rocks," in Mechanical Properties of Rocks, Jerusalem, Israel Program for Scientific Translations, 9-14, 1969.

84. Larocque, G.E. and Favreau, R.F., "Blasting Research at the Mines Branch," Proc. 12th Symp. Rock Mech., Rolla, Missouri, 341-58, 1970.

85. Leeman, E.R., "Absolute Rock Stress Measurements Using a Borehole Trepanning Stress-Relieving Technique," Proc. 6th Symp. Rock Mech., Rolla, Missouri, 407-26, 1964.

86. Lehnhoff, T.F., Patel, M.R., and Clark, G.B., "A Thermal Rock Fragmentation Model," Proc. 15th Symp. Rock Mech., Rapid City, South Dakota, 523-55, 1973.

87. Livingston, C.W., "The Natural Arch, the Fracture Pattern, and the Sequence of Failure in Massive Rocks Surrounding an Underground Opening," Proc. 4th Symp. Rock Mech., Univ. Park, Penn., 197-204, 1961.

88. Lundborg, N., "The Strength-Size Relation of Granite," Int. J. Rock Mech. Min. Sci., 4, 269-72, 1967.

89. Martos, F., "Wassergehalt, and Gesteinsfestigkeit," Proc. 7th Cong. Int. Bur. Rock Mech., Leipzig, 222-43, 1965.

90. Matsushima, S., "On the Flow and Fracture of Igneous Rocks," Disaster Prev. Res. Inst., Kyoto Univ., Bull., 10(36), 1960.

91. Mesri, G., Adachi, K., and Ullrich, C.R., "Pore Pressure Response in Rock to Undrained Change in All Around Stress," Geotechnique, 26(2), 317-30, 1976.

92. Michalopoulos, A.P. and Triandafilidis, G.E., "Influence of Water on Hardness, Strength and Compressibility of Rock," Bull. Assoc. Eng. Geol., XIII(1), 1-22, 1976.

93. Miller, R.P., "Engineering Classification and Index Properties for Intact Rock," University of Illinois, Ph.D. Thesis, 1965.

94. Mitani, T. and Kawai, T., "Experimental Study on Relationship Between Engineering Properties of Rock and Mechanical Drilling Characteristics," Rock Mech. in Japan, II, 124-6, 1974.

95. Mochida, Y., "Rock Properties in the Seikan Tunnel," Rock Mech. in Japan, II, 161-3, 1974.

96. Morrison, R.G.K., "A Philosophy of Ground Control," Ontario Dept. of Mines, Toronto, Canada, 170 pp., 1970.

97. Moye, D.G., "Rock Mechanics in the Investigation and Construction of T.1 Underground Power Station, Snowy Mountains, Australia," in Engineering Geology Case Histories (Trask, P. and Kiersch, G.A., Editors), Numbers 1-5, Geol. Soc. Am., 1964.

98. Nesbitt, R.H., "Laboratory Tests of Rock Cores From Fremont Canyon Tunnel Area - Glendo Unit - Missouri River Basin Project, Wyoming," U.S. Bureau of Reclamation Rept. C945, Denver, Colorado, 1960.

99. Nishihara, M., "Creep of Shale and Sandy Shale," J. Geol. Soc. Japan, 58(683), 373-7, 1952.

100. Obert, L., Windes, S.L., and Duvall, W.I., "Standardized Tests for Determining the Physical Properties of Mine Rock," Bureau of Mines Rept. RI-3891, 67 pp., 1946.

101. Peng, S. and Johnson, A.M., "Crack Growth and Faulting in Cylindrical Specimens of Chelmsford Granite," Int. J. Rock Mech. Min. Sci., 9, 37-86, 1971.

102. Rad, P.F. and McGarry, F.J., "Thermally Assisted Cutting of Granite," Proc. 12th Symp. Rock Mech., Rolla, Missouri, 721-57, 1970.

103. Reichmuth, D.R., "Correlation of Force-Displacement Data With Physical Properties of Rock for Percussive Drilling Systems," Proc. 5th Symp. Rock Mech., Minneapolis, Minn., 33-59, 1962.

104. Ricketts, T.E. and Goldsmith, W., "Dynamic Properties of Rocks and Composite Structural Materials," Int. J. Rock Mech. Min. Sci., 7, 315-35, 1970.

105. Rinehart, J.S., Fortin, J.P., and Burgin, L., "Propagation Velocity of Longitudinal Waves in Rocks. Effect of State of Stress, Stress Level of the Wave, Water Content, Porosity, Temperature, Stratification, and Texture," Proc. 4th Symp. Rock Mech., Univ. Park, Penn., 119-35, 1961.

106. Ringheim, A.S., "Experiences with the Bearpaw Shale at the South Saskatchewan River Dam," Trans. 8th Cong. Large Dams, Edinburgh, I, 529-50, 1964.

107. American Geological Institute, Dictionary of Geological Terms, Anchor Press, 545 pp., 1974.

108. Ruiz, M.D., "Some Technological Characteristics of 26 Brazilian Rock Types," Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, 1, 115-9, 1966.

109. Salas, J.A.J., "Mechanical Resistance," Proc. Int. Symp. Rock Mech., Madrid, 115-29, 1968.

110. Samalikova, M., "Constructive Weathering of Granite on the Dam Profile Near Liberec, Czechoslovakia," Proc. 2nd Int. Cong. Int. Assoc. Eng. Geol., Sao Paulo, I, Paper IV-8, 1974.

111. Schuler, K.W., Lysne, P.C., and Stevens, A.L., "Dynamic Mechanical Properties of Two Grades of Oil Shales," Int. J. Rock Mech. & Min. Sci. & Geomech. Abstr., 13, 91-5, 1976.

112. Schwartz, A.E., "Failure of Rock in Triaxial Shear Test," Proc. 6th Symp. Rock Mech., Rolla, Missouri, 109-52, 1964.

113. Sellers, J.B., "The Measurement of Rock Stress Changes Using Hydraulic Borehole Gauges," Int. J. Rock Mech. Min. Sci., 7, 423-35, 1970.

114. Sibek, V., "Rock Pressure and Deformation of Tertiary Rock During Excavation of Thick Brown Coal Seams by Longwall Method in Strips With Craving," Proc. 3rd Int. Conf. Strata Control, Paris, 422-41, 1960.

115. Lama, R.D. and Vutukuri, V.S., Handbook on Mechanical Properties of Rocks, Vol. I-IV, Trans. Tech. Publications, 1978.

116. Afanas'yev, N.S., Vavakin, V.V., Volarovich, M.P., Levykin, A.I., and Tarkov, A.P., Izv. Akad. Nauk SSSR, Fiz. Zemli, 6, 59-65, 1975.

117. Singh, D.P., "Drillability and Physical Properties of Rocks," Proc. Symp. Rock Mech., Univ. Sydney, 29-34, 1969.

118. Chamberlain, P.G., Van Eeckhout, E.M., and Podnieks, E.R., "Four Factors Influencing Observed Rock Properties," ASTM Spec. Tech. Publ. 599, 16 pp., 1976.

119. Robertson, E.C., "Experimental Study of the Strength of Rocks," Geol. Soc. Am. Bull., 66, 1275, 1955.

120. Handin, J.W. and Hager, R.V., "Experimental Deformation of Sedimentary Rocks Under Confining Pressure," Am. Assoc. Pet. Geol., 42(12), 2892-934, 1958.

121. Handin, J.W. and Hager, R.V., "Experimental Deformation of Sedimentary Rocks Under Confining Pressure," Am. Assoc. Pet. Geol., 41(1), 1-50, 1957.

122. Griggs, D.T., Turner, F.J., and Heard, H.C., "Deformation of Rocks at 500°-800°," Geol. Soc. Am. Mem., 79, 39-104, 1960.

123. Ullao, A., "Field Observations at La Soledad Dam," Trans. 8th Cong. Large Dams, Edinburgh, II, 821-39, 1964.

124. Underwood, L.B., "Tunnelling by Mechanical Miners in Faulted Shale at Oahe Dam," Trans. 7th Cong. Large Dams, Rome, II, 375-404, 1961.

125. Underwood, L.B., "Chalk Foundations at Four Major Dams in the Missouri River Basin," Trans. 8th Cong. Large Dams, Edinburgh, I, 23-47, 1964.

126. Weatherby, R.B. and Faust, L.Y., "Influence of Geologic Factors on Longitudinal Seismic Velocities," Am. Assoc. Pet. Geol. Bull., 19(1), 1-8, 1935.

127. Bredthauer, R.O., "Strength Characteristics of Rock Samples Under Hydrostatic Pressure," Trans. ASME, 79, 695, 1957.

128. Windes, S.L., "Physical Properties of Mine Rock," Bureau of Mines Rept. RI-4459, Part 1, 79 pp., 1949.

129. Wuerker, R.G., "Annotated Tables of Strength of Rock," Trans. AIME, Pet. Paper N-663-G, 12 pp., 1956.

130. Yamaguchi, U., "On the Relationship Between Uniaxial Compressive Strength and Young's Modulus of Rock," J. Soc. Mater. Sci., Jpn., 17(181), 56-61, 1968.

131. Yamaguchi, U. and Morita, M., "Simple Measurement Technique of Dynamic Young's Modulus of Rock by Means of Sound Propagation Method," J. Min. Metall. Inst. Jpn., 85, 319-23, 1969.

132. Youash, Y.Y., "Dynamic Physical Properties of Rocks: Part II, Experimental Results," Proc. 2nd Cong. Int. Soc. Rock Mech., Belgrade, I, 185-95, 1970.

133. Zisman, W.A., "Young's Modulus and Poisson's Ratio With Reference to Geophysical Application," Proc. Nat. Acad. Sci. USA, 19, 653-79, 1933.

134. Znanski, J., "Criteria of the Gradual and Sudden Collapses of Surrounding Rock Into a Mining Excavation," Proc. 3rd Int. Conf. Strata Control, Paris, 211-25, 1960.

135. Znanski, J., "Sklonnosciskal do Tapania," Arch. Gorn., 2(2), 225-40, 1964.

136. Zisman, W.A., "Compressibility and Anisotropy of Rocks At and Near the Earth's Surface," Proc. Nat. Acad. Sci. USA, 19, 666-79, 1933.

137. Aslanyan, A.T., Volarovich, M.P., Levykin, A.I., Beguni, A.T., Artunyan, A.V., and Skvortsova, L.S., "Elastic Wave Velocities in Armenian Basic and Ultrabasic Rocks at High Pressures," Izv. Akad. Nauk SSSR, Fiz. Zemli, 12(2), 30-8, 1976.

138. Bayuk, E.I., Volarovich, M.P., and Skvortsova, L.S., "Velocity of Elastic Waves Under High Pressure in Igneous and Metamorphic Rocks From Various Regions," Nauka Press, 127-37, 1972.

139. Butters, S.W., Dropek, R.K., and Jones, A.H., "Material Properties of Nevada Test Site Tuff and Grout -- With Emphasis on the Mighty Epic Event," Terra Tek, Inc. Rept. DNA-4235-F, Salt Lake City, UT, 426, 1976.

140. Christensen, N.I. and Salisbury, M.H., "Sea Floor Spreading, Progressive Alteration of Layer 2 Basalts, and Associated Changes in Seismic Velocities," Earth Planet. Sci. Lett., 15(4), 367-75, 1972.

141. Christensen, N.I., Fountain, D.M., and Stewart, R.J., "Oceanic Crustal Basement: A Comparison of Seismic Properties of D.S.D.P. Basalts and Consolidated Sediments," Mar. Geol., 15, 215-26, 1973.

142. Baldin, N.E., "An Isotropic Velocities of Elastic Waves in Ultrabasic Rocks of the Kola Peninsula," Tektonofiz. Mekh. Svoistva Gorn. Parod, Akad. Nauk SSR, Inst. Fiz. Zemli, Moscow, 79-88, 1971.

143. Simmons, G., "Velocity of Shear and Compressional Waves in Rocks to 10 kbars," 69, 1117-21, 1123-30, 1964.

144. Preston, D.A., "Correlation of Certain Physical and Chemical Properties in Sedimentary Rocks," Proc. 17th U.S. Symp. Rock Mech., 2A8-1 - 2A8-6, Snowbird, UT, 1976.

145. Schock, R.N., Bonner, B.P., and Louis, H., "Collection of Ultrasonic Velocity Data as a Function of Pressure for Polycrystalline Solids," Univ. of California, Lawrence Livermore Lab. Rept. UCRL-51508, 13 pp., 1974.

146. Simmons, G. and Brace, W.F., "Comparison of Static and Dynamic Measurements of Compressibility of Rocks," J. Geophys. Res., 70, 5649, 1965.

147. Warren, N., "Elastic Constants Versus Porosity for a Highly Porous Ceramic Perlite," J. Geophys. Res., 74(2), 713-9, 1969.

148. Bianchi, L. and Snow, D.T., Ann. Arid Zone (Arid Zone Res. Assoc. of India), 8(2), 231-45, 1969.

149. Brace, W.F., "Some New Measurements of Linear Compressibility of Rocks," J. Geophys. Res., 70, 391-8, 1965.

150. Somerton, W.H., Ward, S.H., and King, M.S., "Physical Properties of Mohole Test Site Basalt," J. Geophys. Res., 68(3), 849-56, 1963.

151. Byers, F.M., Jr., "Porosity, Density and Water Content Data on Tuff of the Oak Spring Formation from the U12E Tunnel System, Nevada Test Site, Nye County, Nevada," U.S. Geological Survey Rept., 37 pp., 1961.

152. Michalopoulos, A.P. and Triandafilidis, G.E., "Influence of Water on Hardness, Strength and Compressibility of Rock," AEG Bull., 13(1), 1-22, 1976.

153. Davis, S.N., Flow Through Porous Media (DeWeist, R.J.M., Editor), Academic Press, New York, 34-89, 1969.

154. Delisle, G., "Determination of Permeability of Granite Rocks in GT-2 from Hydraulic Fracturing Data," Los Alamos Scientific Lab. Informal Rept. LA-6169-MS, 5 pp., 1975.

155. Weatherby, B.B., Born, W.T., and Harding, R.L., "Granite and Limestone Velocity Determination in Arbuckle Mountains, Oklahoma," Am. Assoc. Pet. Geol. Bull., 18, 106, 1935.

156. Emerick, W.L., "Interim Geological Investigations in the U12e.04 Tunnel, Nevada Test Site, Nye Co. Nevada," U.S. Geological Survey Rept. TFI 776, 38 pp., 1962.

157. Emerick, W.L., Dickey, D.D., and McKeown, F.A., "Interim Geological Investigations in the U12e.04 Tunnel, Nevada Test Site, Nye Co., Nevada," U.S. Geological Survey Rept. TFI 776, 27 pp., 1962a.

158. Emerick, W.L., Hasler, J.W., and Bowers, W.E., "Outline of the Geology of the U12g.01 Tunnel, Nevada Test Site, Nye Co., Nevada," U.S. Geological Survey Tech. Lett. Area 12, 21 pp., 1962b.

159. Emerick, W.L., Snyder, R.P., and Hoover, D.L., "Additional Physical Property Data, U12g.01 Tunnel, Nevada Test Site, Nye Co., Nevada," U.S. Geological Survey Tech. Lett. Area 12, 3 pp., 1962c.

160. Franklin, J.A. and Hoeck, E., "Developments in Triaxial Testing Technique," Rock Mech., 2, 223-8, 1970.

161. Gondouin, M. and Scala, C., "Streaming Potential and the SP Log," Trans. Am. Inst. Min. Metall. Eng., Paper 8023, 213, 170-9, 1958.

162. Hanley, E.J., DeWitt, D.P., and Roy, R.F., "The Thermal Diffusivity of Eight Well-Characterized Rocks for the Temperature Range 300-1000 K," Eng. Geol., 12, 31-47, 1978.

163. Izett, G.A., "Granite Exploration Hole, Area 15, Nevada Test Site, Nye Co., Nevada -- Interim Report, Part C, Physical Properties," U.S. Geological Survey, Trace Elements Memorandum Rept. 836-C, 3711, 1960.

164. Keller, G.V., "Physical Properties of Tuffs of the Oak Spring Formation, Nevada," U.S. Geological Survey Prof. Paper 400-B, 396-400, 1960.

165. Kessler, D.W., Insley, H., and Sligh, W.H., "Physical Mineralogical & Durability Studies on the Building & Monumental Granite of the U.S.," J. Res. Natl. Bur. Stand., 25, 161-206, 1940.

166. Manger, G.E., "Porosity and Bulk Density of Sedimentary Rocks," Geol. Surv. Bull. (U.S.), 55 pp., 1963.

167. Mellor, M., "Strength and Deformability of Rocks at Low Temperatures," Cold Regions Research and Engineering Lab. Rept. CRREL-RR-294, Hanover, NH, 78 pp., 1971.

168. Morris, D.A. and Johnson, A.I., "Summary of Hydrologic and Physical Properties of Rock and Soil Material as Analyzed by the Hydrologic Laboratory of the USGS," Geol. Surv. Water-Supply Pap. (U.S.) 1839-D, 1948-60, 1967.

169. Neglia, S., "Migration of Fluids in Sedimentary Basins," Am. Assoc. Pet. Geol. Bull., 63, 573-97, 1979.

170. Norton, D. and Knapp, R., "Transport Phenomena in Hydrothermal Systems: The Nature of Porosity," Am. J. Sci., 297, 913-36, 1977a.

171. Ohle, E.L., "The Influence of Permeability on Ore Distribution in Limestone and Dolomite," Econ. Geol., 46(7), 667-706, 1951.

172. Potter, J.M., "Experimental Permeability Studies at Elevated Temperature and Pressure of Granitic Rocks," Los Alamos Scientific Lab. Rept. LA-7224-T, 101 pp., 1978.

173. Pratt, H.R., Black, A.D., Brace, W.F., and Norton, D.L., "In-Situ Joint Permeability in a Granite," EOS, Trans. Am. Geophys. Union, 55(4), 433, 1974.

174. Rasmussen, W.C., "Permeability and Storage of Heterogeneous Aquifers in the United States," Int. Assoc. Sci. Hydrol. Publ., 64, 317-25, 1964.

175. Saucier, K.L., "Tests of Rock Cores, Mountain Home, Idaho, and Fairchild, Washington, Areas," U.S. Army Engineer Waterways Experiment Station, Misc. Paper C-69-12, 291 pp., 1969.

176. Schoeller, H., "A Monographic Compilation of Data on the Occurrence, Migration, and Properties of Ground Waters, the Characteristics of Aquifers and Watersupply Investigations, Exploitations, and Reserves," in Les eaux Souterraines, Masson, Paris, 642 pp., 1962.

177. U.S. Geological Survey, "Computer Punch Card: Experimental Results," 1964.

178. Williams, W.P., Emerick, W.L., Davis, R.E., and Snyder, R.P., "U.S. Geological Survey Investigations in Yucca Flat, Nevada Test Site. Part C -- The Underground Test Media of Yucca Flat," U.S. Geological Survey Rept. NT Pt. C, 251 pp., 1963.

179. Winograd, I.J., "Hydrogeology of Ash Flow Tuff: A Preliminary Statement No. 4," Water Resour. Res., 7, 994-1006, 1971.

180. Winograd, I.J. and Thordarson, W., "Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California With Special Reference to the Nevada Test," U.S. Geological Survey Prof. Paper 712-C, 126 pp., 1975.

181. Boardman, C.R. and Skrove, J., "Distribution in Fracture Permeability of a Granitic Rock Mass Following a Contained Nuclear Explosion," J. Pet. Technol., 18(5), 619-23, 1966.

182. Houser, F.N., "Some Physical Property Data of Samples From U15a Site, Nevada Test Site," U.S. Geological Survey Tech. Lett. Area 15-2, 4 pp., 1962.

183. Hughes, D.S. and Cross, J.H., "Elastic Wave Velocities in Rocks at High Pressure and Temperature," Geophysics, 16(4), 577-93, 1951.

184. Hughes, D.S. and Maurette, C.G., "Variation of Elastic Wave Velocities in Basic Igneous Rocks With Pressure and Temperature," Geophysics, 22(1), 23-31, 1956.

185. Mason and Bommel, J. Acoust. Soc. Am., 28, 930, 1956.

186. Volarovich, B. and Pavlogradsky, V.A., "Study of the Compressibility of Igneous Rocks at Pressures up to 5000 kg cg/cm^2," Bull. (Izv.) Acad. Sci. USSR, Geophys. Ser., 5, 486-92, 1959.

187. Hughes, D.S. and Jones, H.J., "Variation of Elastic Moduli of Igneous Rocks With Pressure and Temperature," Geol. Soc. Am. Bull., 61(8), 843-56, 1950.

188. Brace, W.F., "Relation of Elastic Properties of Rocks to Fabric," J. Geophys. Res., 70(2), 391-8, 1965.

189. Birch, F. and Bancroft, D., "The Effect of Pressure on the Rigidity of Rocks," J. Geophys. Res., 46, 59-87, 113-41, 1938.

190. Bridgman, P.W., "The Thermal Conductivity and Compressibility of Several Rocks Under High Pressures," Am. J. Sci., 7, 81-102, 1924.

191. Griggs, D.T., Turner, F.J., and Heard, H.C., "Deformation of Rocks at 500-800°C," Geol. Soc. Am. Mem., 79, 30-104, 1960.

192. Handin, J. and Hager, R.V., "Experimental Deformation of Sedimentary Rocks Under Confining Pressure," Am. Assoc. Pet. Geol. Bull., 42, 2892-934, 1958.

193. Heard, H.C., Abey, A.E., Bonner, B.P., and Schock, R.N., "Mechanical Behavior of Dry Westerly Granite at High Pressure," Lawrence Livermore Lab. Rept. UCRL-5164, 14 pp., 1974.

194. Krech, W.W., Henderson, F.A., and Hjelmstad, K.E., "A Standard Rock Suite for Rapid Excavation Research," Bureau of Mines Rept. BM-RI-7865, 1974.

195. Birch, A.F., "The Velocity of Compressional Waves in Rocks to 10 Kilobars," J. Geophys. Res., 66(7), Pt. 2, 2199-224, 1961.

196. Adams, L.H. and Williamson, E.D., "On the Compressibility of Minerals and Rocks at High Pressure," J. Franklin Inst., 195, 475, 1923.

197. Stowe, R.L., "Strength and Deformation Properties of Granite, Basalt, Limestone and Tuff at Various Loading Rates," U.S. Army Corps of Engineers, Waterways Exp. Station, Misc. Paper C-69-1, 1969.

198. Windes, S.L., "Physical Properties of Mine Rock," Bureau of Mines Rept. BM-RI-4727, 8-11, 1950.

199. Weyermann, W., "Resultats de l'Observation des Sous-Pressiors du Barrage de l'Alto Rabagao (Portugal)," Trans. 10th Cong. Large Dams, Montreal, Vol. II, Q. 37, R. 22, 369-90, 1970.

200. Zaruba, Q. and Bukovansky, M., "Mechanical Properties of Ordovician Shales of Central Bohemia," Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, Vol. I, 421-4, 1966.

201. Rocha, M., Serafim, J.L., and Da Silveira, A.F., "Deformability of Foundation Rocks," Trans. 5th Cong. Large Dams, Paris, Vol. III, Q. 18, R. 75, 1955.

202. Serafim, J.L. and Bollo, M.F., "Importance of Studies With Elastic Waves in the Geotechnical Exploration of the Foundations of Concrete Dams," Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, Vol. II, 655-60, 1966.

203. Shannon and Wilson, Inc., "Report on In-Situ Rock Tests, Dworshak Dam Site for U.S. Army Engineers District, Walla Walla, Corps of Engineers, Seattle, Washington," 1964.

204. Holland, C.T., "Design of Pillars for Overburden Support-Part I," Min. Congr. J., 1954.

205. Rocha, M., "Mechanical Behaviour of Rock Foundations in Concrete Dams," Trans. 8th Cong. Large Dams, Edinburgh, Vol. I, 785-831, 1964.

206. Martin, R.A., "The Effect of Moisture on the Compressive and Tensile Strength on a Variety of Rock Materials," Univ. of Missouri at Rolla, M.S. Thesis, 121 pp., 1966.

207. Pahl, A. and Albrecht, H., "Felsmechanische Untersuchungen Zur Beurteilung der Standfestigkeit Grosser Felskavernen," Proc. 2nd Cong. Int. Soc. Rock Mech., Belgrade, Vol. II, 767-72, 1970.

208. Johnson, in Materials of Construction, John Wiley & Sons, New York, NY, 252-8, 1939.

209. Hunt, R.W., Leach, R.E., Curro, J.R., Jr., Gatz, J.L., and Stowe, R.L., U.S. Army Corps Engineers, Waterways Experiment Station, Misc. Paper S-71-2, 335 pp., 1971.

210. Onodera, T.F., "Dynamic Investigation of Foundation Rocks In-Situ," Proc. 5th Symp. Rock Mech., Minneapolis, Minn., 517-33, 1962.

211. Mellor, M., "Mechanical Properties of Rocks at Low Temp.," Int. Conf. Permafrost, 2nd, Yakutsk, USSR, 25 pp., 1973.

212. Summers, D.A., "Water Jet Cutting Related to Jet and Rock Properties," Proc. 14th U.S. Symposium on Rock Mechanics, 569-88, 1973.

213. Saucier, K.L. and Ainsworth, D.L., U.S. Army Corp of Engineers, Waterways Experiment Station Misc. Paper C-69-3, 286 pp., 1969.

214. Saucier, K.L. and Crisp, R.W., U.S. Army Corps of Engineers, Waterways Experiment Station Misc. Paper C-69-16, 122 pp., 1969.

215. Müller, L., Der Feisbau, I. Stuttgart. Ferdinand Enke Verlag., 624 pp., 1960.

216. Barnes, H., Hinrichs, E.N., McKeown, F.A., and Orkild, P.P., "U.S. Geological Survey Investigations in Yucca Flat, Nevada Test Site. Part A -- Geology of the Yucca Flat Area," U.S. Geological Survey Rept. NTS-45, Part A, 196 pp., 1963.

217. Lane, R.G.T., "Rock Foundations: Diagnosis of Mechanical Properties and Treatment," Trans. 8th Cong. Large Dams, Edinburgh, Vol. I, R. 8, Q. 28, 141-65, 1964.

218. Hasler, J.W. and Emerick, W.L., U.S. Geological Survey Tech. Lett. Area 12-8, 14 pp., 1966.

219. Anderson, R.E., "A Study of the Structure Between Pahute Mesa and the Toryabe Range, Nevada," U.S. Geological Survey Tech. Lett. NTS-182, 38 pp., 1967.

220. Kitsunezaki, C., "In-Situ Determination of Variation of Poisson's Ratio in Granite Accompanied by Weathering Effect and Its Significance in Engineering Projects," Disaster Prev. Res. Inst., Kyoto Univ., Bull., 15(92), Pt. 2, 1965.

221. Japanese National Committee on Large Dams, "Present Status of Measurements of Structural Behaviour of Dams in Japan," Trans. 6th Cong. Large Dams, New York, Vol. 2, R. 25, Q. 21, 301-57, 1958.

222. Bacon, L.O., "A Method of Determining Dynamic Tensile Strength of Rock at Minimum Loading," Bureau of Mines Rept. BM-RI-6067, 22 pp., 1962.

223. Mellor, M. and Rainey, R., "Tensile Strength of Rocks at Low Temperatures, Preliminary Data Report," U.S. Army Terrestrial Sciences Center, Unofficial Memorandum, 34 pp., 1968.

224. Iida, R., Okamoto, R., and Yasue, T., "Geological Rock Classification of Dam Foundation," Rock Mech. Jpn., I, 161-3, 1970.

225. Cogan, J., "The Creep of Weak Rocks in the Burgin Mine," Stanford Univ., Ph.D. Thesis, 315 pp., 1975.

226. Cording, E.J., Hendron, A.J., and Deere, D.U., "Rock Engineering for Underground Caverns," Proc. Symp. Underground Rock Chambers, Phoenix, Arizona, 567-600, 1971.

227. Dvorak, A., "Tests of Anisotropic Shales for Foundation of Large Bridge," Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, Vol. II, 537-41, 1966.

228. Fernandes, L.H.G. and De Sousa, A.A.C., "Le Comportement du Barrage de Salamonde Dans les Premiers 15 Mois du Remplissage de sa Retenue," Trans. 5th Cong. Large Dams, Paris, Vol. III, Q. 16, R. 18, 261-72, 1955.

229. Gimm, W.A.R., Richter, E., and Rosietz, G.P., "Uber das Verformungs- und Festigkeitsverhalten des Gebirges bei Grossversuchen im Eisenerzbergbau," Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, Vol. I, 457-63, 1966.

230. GTCNF (Groupe de Travail du Comite National Francais, France), "La Deformabilite des Massifs Rocheux Analyse et Comparaison des Resultats," Trans. 8th Cong. Large Dams, Edinburgh, Vol. II, R. 15, Q. 28, 287-312, 1964a.

231. Habetha, E., "Large Scale Shear Tests for the Waldeck-II Pump Fed Storage Station Construction Project," Proc. 2nd Int. Cong. Int. Assoc. Eng. Geol. Sao Paulo, Vol. I, Paper IV-35, 1974.

232. Hayashi, M., Fuziwara, Y., and Komoda, H., "Dynamic Deformability and Viscosity of Rock Mass and Rock Fill Material Under Repeated Loadings In-Situ and Triaxial Test," Rock Mech. Jpn., Vol. II, 84-6, 1974.

233. Chong, K.P., Smith, W.J., and Khaliki, B.A., "Creep and Relaxation of Oil Shale," Proc. 19th U.S. Symposium on Rock Mechanics, Vol. I, 414-8, 1978.

APPENDIX II

SECTION 2.

FEASIBILITY STUDY

DATA FOR NUCLEAR WASTE DISPOSAL
THE THERMOPHYSICAL AND ELECTRICAL PROPERTIES OF BASALT, GRANITE, SHALE, AND TUFF

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PART I. THERMOPHYSICAL PROPERTIES OF BASALT, GRANITE, SHALE, AND TUFF

NOMENCLATURE

A	a constant: $A = [(Q/4\pi\lambda)\ln D] + \ldots$
A_o	lattice constant
a	probe radius (in eq. 7)
a,b,c	lattice spacings
B	ratio of heat capacities of medium and probe material
c	thermal conductance per unit length
c_0, c_1	calibration constants in eq. 10
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
D	defined as: $D = 4\alpha/1.7811\ a^2$ (in eq. 7); also diameter of specimen bar
d	separation of the lattice planes (in eq. 24)
d_p	diameter of the p'th fringe
f	focal length of lens in interferometer
h	defined as: $h = \lambda/ac$
h,k,ℓ	Miller indices for the planes
L	length of specimen bar; also distance between surfaces
L_{293}	length at 293 K
$\Delta L/L$	coefficient of linear expansion (incremental)
ℓ	thickness of specimen
$\ln$	logarithm to the base e
N	number of fringes
n	refractive index
P	pressure
p	volume proportion of constituents in a two component material
Q	heat flux
r	radius of bar specimen; also ratio of thermal conductivities of a two component material: $r = \lambda_c/\lambda_f$
S	distance between fringes
T	absolute temperature
t	time
V	sound velocity

W	perpendicular distance between the specimen and the line that joins the separators in a Fizeau interferometer
x	distance along specimen

Greek Symbols

α	thermal diffusivity
α,β,γ	angles between lattice axis (in eq. 24)
β_ℓ	coefficient of thermal linear expansion
β_v	coefficient of thermal volumetric expansion
γ_G	Grüneisen parameter
Δ	a finite change in a quantity
ε	coefficient of extinction
θ	angle between the direction of incident or reflected ray and the direction normal to the surface
λ	thermal conductivity
λ_b	thermal conductivity of brass bar
λ_c	thermal conductivity of continuous phase (matrix) of a two component material
λ_f	thermal conductivity of the fluid phase
λ_ℓ	lattice, or phonon, conduction coefficient
λ_R	thermal conductivity of rock
λ_v	wavelength of light in vacuum
ν	a finite change in a quantity
π	mathematical constant: $\pi = 3.1416$
ρ	density
σ	Stefan-Boltzmann constant: $\sigma = 1.38054 \times 10^{-23}$ J k^{-1}
τ	defined as: $\tau = \alpha t/a^2$

INTRODUCTION

The thermophysical properties of interest are the thermal conductivity, the expansion coefficient, and thermal capacity (the product of specific heat and density). Thermal diffusivity is not an independent property since it is the ratio of thermal conductivity to thermal capacity. The various factors involved in the measurement and accuracy of these properties are discussed, together with illustrative examples.

DEFINITIONS AND THEORETICAL CONSIDERATIONS

THERMAL CONDUCTIVITY

The lattice, or phonon, transfer coefficient, λ_ℓ, which is usually referred to as the thermal conductivity of the material, is defined as the ratio of heat flow per unit area to temperature gradient and is connected to other physical properties, including seismic velocities, by means of the Grüneisen parameter γ_G. The relationship is shown in eq. (1) where C_v is the specific heat at a constant volume, V is the mean sound velocity, A_o is the lattice constant, β_v is the volumetric thermal expansion coefficient, and T the absolute temperature.

$$\lambda_\ell = \frac{1}{3} \frac{C_v V A_o}{\beta_v \gamma_G} \frac{1}{T} \tag{1}$$

The Grüneisen parameter is essentially a measure of the fractional change of pressure on heating a material at constant volume, so that seismic velocity and thermal conductivity are related by means of the effect of pressure on the lattice constant.

Strictly speaking, eq. (1) applies only at temperatures well above the Debye temperature and refers only to very simple isotropic single crystals. There is some debate as to whether the temperature dependence is as T^{-1} (three phonon mode) or $T^{-5/4}$ (four phonon mode). The argument is largely academic in our context since by the time the temperature is high enough to worry about the difference, we are in a region where λ_r is dominant.

Since the range of thermal conductivities of minerals spans only one or two orders of magnitude, and the range from gases to pure metals is only five of six orders of magnitude, compared with more than 20 orders of magnitude for electrical conductivities, the influence of compositional and structural variations is far less than in the case of electrical properties.

COEFFICIENT OF LINEAR THERMAL EXPANSION

The linear thermal expansion coefficient, β_ℓ, is defined as the fractional change in length per deg K temperature change. The volume expansion coefficient, β_v, is similarly defined as the fractional volume change per deg K. The relation between the two is obvious.

THERMAL CAPACITY

Thermal capacity is defined as the amount of heat per unit volume required to heat the material one degree K and is the product of the specific heat at constant pressure, c_p, and density, ρ. The value of accepting this as a thermal property, rather than just the specific heat, is that the product ρc_p has a built-in, self-compensating factor. The great majority of minerals and impervious rocks, ρc_p lies within 20% of 2.3 W s $cm^{-3}K^{-1}$. For porous rocks, the thermal capacity can be found by weighting the thermal capacity of the pore fluid and the matrix material according to their volume proportions.

THERMAL DIFFUSIVITY

Thermal diffusivity, α, is defined as the ratio of thermal conductivity to thermal capacity, eq. (2). Because of the above-mentioned relative constancy of ρc_p, it is usually simpler and more accurate to obtain α by measuring the conductivity by an established method and determining α from eq. (2).

$$\alpha = \frac{\lambda_\ell}{\rho c_p} \tag{2}$$

Measurement of diffusivity can be made directly by the "flash" method. In this technique, an instantaneous energy source is applied to a specimen in the form of a thin disk and the temperature rise as a function of time is measured in the back face of the specimen. The instantaneous source can be a high energy pulse or laser applied to the surface of a disk shaped specimen, this latter now being a popular technique [17,19,25].

In actual practice, a heat source, such as flash tube or laser, supplies a flash of energy to the front face of a thin disk specimen and the temperature as a function of time at the rear face is automatically recorded. The thermal diffusivity is obtained from the thickness of the specimen, ℓ, and a specific time, $t_{1/2}$, at which the back face temperature reaches half its maximum value by the expression

$$\alpha = 1.37\ \ell^2/\pi^2 t_{1/2}\ . \tag{3}$$

The thermal conductivity of the specimen is then calculated by the relation

$$\lambda = \rho \alpha c_p \tag{4}$$

where λ is the thermal conductivity, ρ is the density, and c_p is the specific heat at constant pressure.

In all cases, the basic assumption is that a very high pulse of energy lasts for an infinitesimally short time. Recent developments concern the corrections required for finite pulse time effects [2,12,28].

Results from the "flash" technique appear to be reasonably consistent with different workers reporting values within about 10% of each other on apparently identical materials. However, there does not appear to have been any systematic comparison of diffusivity values obtained using the "flash" technique with those obtained using a standard temperature-time curve technique on the same material. This omission may not have serious implications for measurements made at ordinary temperatures and pressures, but may have considerable significance for the increasing number of experiments being made at high pressures and high temperatures.

MEASUREMENT METHODS FOR THERMAL CONDUCTIVITY

It is convenient to divide the experimental methods into two broad groups: (a) one dimensional steady state, comparator types, and (b) two dimensional (cylindrical), absolute type. Although it is possible to use one dimensional transient techniques, none are used, or have been used, to a significant extent.

By far, the great majority of steady state techniques (one dimensional) are comparative methods, the comparison being made in one of two ways. In both cases negligible lateral heat loss is assumed and the unknown disk is usually placed at the center of a geometrically symmetrical arrangement with a constant temperature difference maintained across the system [3,4]. The thermal contact resistance is either kept small enough to be ignored or else determined and eliminated by measurements on samples of different thicknesses, or by measurements on one sample but using different conductivity fluids in the interface region. In the following discussion, negligible contact resistance is assumed except in the section specifically discussing the errors which might arise if there are unsuspected contact effects.

DIVIDED BAR TECHNIQUE

Two bars are used, each several centimeters long, and a typical experiment consists of measuring the temperature gradient, dT/dx, along the reference bar, usually brass, of known conductivity, λ_b [7]. The amount of heat per unit area per unit time flowing down the bar is determined from

$$Q = \lambda_b \left(\frac{dT}{dx}\right)_b \tag{5}$$

The temperature drop across the unknown specimen is measured, and since its thickness and the heat flowing through it are known, the conductivity of the unknown can be determined by using eq. (5) with a suitable change in subscript.

STACKED DISKS METHOD

The unknown sample is usually sandwiched between two reference disks of known conductivity [8], and the temperature differences across each of the disks are determined. That is, the temperature gradient through each of the disks is found, and once again, since the conductivity of the standards are known, the conductivity of the unknown sample can be determined. The reference material may be an artificial material with a conductivity, calibrated against a standard such as quartz, in the middle of the range of rock conductivities, or it could be a standard material itself.

In both cases the calibration materials used by the great majority of researchers are fused quartz and crystalline quartz cut so that the heat flow is perpendicular to the optic axis.

CYLINDRICAL HEAT FLOW TECHNIQUE

There are again two basic approaches - the transient and the steady state cases. In both cases a long heating probe supplies energy at the rate of Q per unit time per unit length, the length, L, being considerably greater than the diameter (D); usually L > 50D.

In the steady state case temperature sensors are located at known radii, r_1 and r_2, and from the temperature difference, (T_1-T_2), between them the conductivity can be determined from eq. (6) once the steady state has been reached.

$$\lambda = \frac{Q}{2\pi} \frac{\ell n(r_2/r_1)}{T_1 - T_2} \qquad (6)$$

Frequently, a true steady state is not reached in which case the same equation may be used for the quasi-steady state case as can readily be shown by manipulation of eq. (19) in Chapter 13, Section 5 of ref. [11].

In the transient case the rise of temperature with time is monitored and the conductivity determined from eq. (7).

$$\Delta T = \frac{Q}{4\pi\lambda} \left[2h + \ell n(Dt) - (4h - B)\ (2B\tau)^{-1} + (B - 2)\ (2B\tau)^{-1}\ \ell n(Dt)\right] \qquad (7)$$

where $D = 4\alpha/1.7811\ a^2$, $\tau = \alpha t/a^2$, $h = \lambda/ac$, B is twice the ratio of thermal capacities of the medium and probe material, a is the probe radius, t is time, and c is the thermal conductance per unit length of the contact layer.

Equation (7) is for a probe of finite radius. Such probes are used for the in-situ determination of thermal conductivity [6], with or without the presence of a thermal contact resistance at the boundary. In this case a log-log plot is made from which both λ and τ (and, therefore, thermal capacity) may be determined from the displacement of the origin [20].

If the radius of the probe is very small, so that τ is always large, even for relatively small times, then the above equation reduces to the familiar line source form, eq. (8).

$$T = \frac{Q}{4\pi\lambda}\ \ell n\ t + A \qquad (8)$$

where the constant $A = [(Q/4\pi\lambda)\ \ell n\ D] + \ldots$. It can readily be seen that a plot of temperature rise versus $\ell n\ t$ should be a straight line in the early part of the experiment from the slope of which the conductivity may be determined, eq. (9).

$$\lambda = \frac{Q}{4\pi L} \frac{\ell n(t_2/t_1)}{(T_2 - T_1)} \qquad (9)$$

This is the standard technique used for ocean sediments [29] but has been used only occasionally for measurement on continental materials [31]. Care has to be exercised since there are some "false" asymptotes and the best method of reduction is to record the temperature-time data continuously and calculate incremental conductivities using eq. (9). The most reliable result occurs where the value of the conductivity is a minimum.

Since the constant contains the diffusivity, once λ has been determined then τ (and hence ρc_p) can be found from the intercept of the best straight line.

DISCUSSION OF SOURCES OF ERROR IN THERMAL CONDUCTIVITY MEASUREMENTS

Sampling Errors

Because of the small scale heterogeneity of most rocks, particularly those that are coarse grained or bedded, an important source of error in establishing a conductivity of rock in bulk is the age-old one of finding representative samples. In some cases, conductivities measured on contiguous samples, of approximately 10 cm^3 volume, can give conductivities that differ by 50% even though each sample value has a precision of 1%.

For this reason, few rock conductivity apparatuses are designed to give high accuracy, say better than 1%. Rather they are designed to give results rapidly to within 5% and the average of many samples taken to give a unit conductivity.

Contact Resistance Error

One frequently overlooked but sometimes important source of error which is always present and cannot be removed is the contact resistance at the sample-equipment interfaces [5]. If a relatively high conductivity is used in the interface, its thermal resistance can be made quite small relative to the thermal resistance of the sample and the effect ignored. Water is a good fluid to use since its conductivity is relatively high and in many cases the requirement is for the conductivity of water saturated rocks. However, if air or oil are used, then large errors can result, especially if the rock is coarse grained and porous. It may be necessary to use these fluids if the conductivity of oil saturated rocks is required or if the material is so metastable that it disintegrates when soaked in water.

If enough material is available the contact resistance can be found from measurements on samples of significantly different thicknesses, the basic assumption being that the surface finish and conductivity of each sample is the same.

If there is only sufficient material for one sample, it is possible to determine a contact resistance correction from measurements using saturation (nondisintegrating) fluids of different conductivities.

MEASUREMENT METHODS FOR THERMAL EXPANSION

PUSH-ROD DILATOMETERS

The push-rod dilatometer method for measuring thermal expansion is experimentally simple, reliable, and easy to automate [13]. With this method, the expansion of the specimen is transferred out of the heated zone to an extensometer by means of rods (or tubes) of some stable material. The expansion of the specimen is given by

$$\frac{\Delta L}{L_{293}} = c_0 \frac{(\Delta L)_a}{L_{293}} + c_1 \tag{10}$$

where $(\Delta L)_a$ is the apparent change in length as calculated from the difference between the extensometer readings at two different temperatures, and c_0 and c_1 are calibration constants for the system. If the reference rod is made the same length as the push rod and a second specimen placed on the base plate, the dilatometer will measure the difference between the specimens [27]. The difference, or differential expansion, is given by

$$\frac{(\Delta L)_r}{L_{293}} - \frac{(\Delta L)_s}{L_{293}} = c_0 \frac{(\Delta L)_a}{L_{293}} + c_1 \tag{11}$$

When used this way the dilatometer can have a very high sensitivity. This technique is also very useful for quality control measurements and for studying phase transitions.

One of the most common sources of error in using dilatometers is the measurement of temperature. All too often the temperature that is measured is not the temperature of the specimen. This is especially true in measurements made while the temperature is changing. If a thermocouple is used, care must be taken to ensure that its junction and specimen are at the same temperature. They can be at different temperatures even if in contact with each other. Another common source of error, especially for flexible materials or materials near their softening temperatures, is deformation under the load of the push rod. Special techniques such as increasing sample diameter, reducing push rod pressure, and using horizontal mounts must be used for these soft materials.

The uncertainty of this method depends on the quality of the push rod used and precision of construction. Results of two or three percent uncertainty may be achieved routinely.

INTERFEROMETER TECHNIQUE

These methods are based on the interference of monochromic light reflected from two surfaces [21] that are separated by a specimen or by the combination of a specimen and a reference material. The general condition for interference is

$$2nL \cos \theta = N\lambda_{\nu} \tag{12}$$

where n is the index of refraction of the atmosphere between the surfaces, L the distance between the two surfaces, θ the angle between the direction of the incident rays and the direction normal to the surfaces, N the order of interference, and λ_{ν} the wavelength of the light in vacuum. Monochromatic light sources that may be used include cadmium, helium, mercury, and sodium low-pressure discharge lamp [10] and a stabilized He-Ne laser [26].

If slightly inclined surfaces are illuminated with collimated light and viewed at normal incidence (θ=0 for all rays), fringes of equal inclination are observed. When the surfaces are flat the fringes will be straight; otherwise, they are determined by the contour of the surfaces. This type of interference is used in the Fizeau interferometer [1]. If plane-parallel surfaces are illuminated with an extended source (θ will vary), fringes of equal inclincation are observed. This type of interference (concentric rings) is used in the Fabry-Perot interferometer [16].

When an interferometer is used to measure thermal expansion, the expansion of the specimen is given by

$$\frac{\Delta L}{L} = \frac{\lambda_{\nu}}{2nL} \frac{\Delta N}{\cos \theta} - \frac{\Delta n}{n} \tag{13}$$

where ΔN is the number of the fringes that pass a fiducial mark and Δn is the change of refractive index. A useful approximation for the refractive index is

$$n = 1 + (n_r - 1) \frac{T_r P}{P_r T} \tag{14}$$

where n_r is the index at the reference temperature T_r and the reference pressure P_r. In vacuum or in a sufficiently low-pressure atmosphere

$$\frac{\Delta L}{L} = \frac{\lambda_\nu}{2L} \frac{\Delta N}{\cos \theta} \tag{15}$$

In a Fizeau interferometer (straight fringes) the fractional part of ΔN is easily determined from measurements of the position of the fiducial mark between two fringes. In the Fabry-Perot interferometer (circular fringes) the fractional part, ν, is given by

$$\nu = 1 - p + \frac{nLd_p{}^2}{f^2 \lambda_\nu} \tag{16}$$

where d_p is the diameter of the pth fringe (counted from the center of the concentric pattern) and f is the focal length of the lens that forms the pattern. If measurements are made on the second and fourth fringes, the fractional part is

$$\nu = \frac{3d_2^2 - d_4^2}{d_4^2 - d_2^2} \tag{17}$$

The number of fringes that move past a reference point during the expansion of a specimen can be counted by eye or automatically by photographic [30] or photoelectric [15] techniques. Another way of determining ΔN is by finding the value of N at each temperature. This can be done by using at least three different wavelengths [10]. From eq. (12) it can be seen that

$$(N_1 + \nu_1)\lambda_1 = (N_2 + \nu_2)\lambda_2 = (N_3 + \nu_3)\lambda_3 \tag{18}$$

where N_1, N_2, and N_3 are the fringe integers and ν_1, ν_2, and ν_3 are the fringe fractions for each of the three wavelengths. In the method of exact fractions a value is guessed for N_1 ($\sim 2nL/\lambda_1$) and using the measured value of ν_1 the values of $(N_2 + \nu_2)$ and $(N_3 + \nu_3)$ are calculated. This procedure is repeated with different values of N_1 until the calculated values of ν_2 and ν_3 agree with their measured values. If N is known, then

$$\frac{\Delta L}{L} = \frac{\Delta N}{N} - \frac{\Delta n}{n} \tag{19}$$

The Fizeau interferometer can be used to measure either the absolute or relative expansion of a specimen. In the relative method a pedestal of one material fills most of the space within a ring or cylinder of a second material. The pedestal is preferably made of a reference material. While the ring supports the optical flat, the interference is formed by reflections from the optical flat and the top surface of the pedestal. Since the reflecting surfaces are close together this method has three advantages: (1) the fringes are bright and well defined; (2) the change of the refractive index of the gas within the small space does not affect the measurements; and (3) longer specimens can be used with a corresponding increase in sensitivity. The thermal expansion is given by

$$\left(\frac{\Delta L}{L}\right)_s = \frac{\lambda_\nu \Delta N}{2nL_s} + \frac{L_R}{L_s}\left(\frac{\Delta L}{L}\right) + \frac{L_s - L_R}{L_s}\frac{\Delta n}{n} \qquad (20)$$

where the subscripts s and R refer to the specimen and reference materials. When $L_R \sim L_s$ the last term can be ignored.

If one or all three of the separators in a Fizeau interferometer expand differently, the difference will cause a rotation and/or change in the spacing of the fringes. In the first case where the two similar separators made from a reference material are exactly the same length the difference in expansion of the other material is given by

$$\left(\frac{\Delta L}{L}\right)_s - \left(\frac{\Delta L}{L}\right)_R = \frac{W\lambda_\nu}{2L_s}\left[\frac{1}{n_2 S_2} - \frac{1}{n_1 S_1}\right] \qquad (21)$$

where W is the perpendicular distance between the specimen and the line that joins the separators and S is the distance between fringes.

When the optical flats of a Fabry-Perot interferometer are made highly reflecting the multiple reflected beams cause a great increase in sharpness of the fringes. This sharpness results in a higher sensitivity in the measurement of fringe fractions and, hence, in the expansion measurements. The sensitivity of a polarizing interferometer [14] is also higher because the measurement of the polarization angle is a more sensitive way of determining a fringe fraction. The laser is an extremely efficient source of radiation for this type of interferometer because it can be constructed to emit a polarized beam. This method is inherently capable of producing results of very high accuracy if the samples are properly prepared.

X-RAY METHODS

These methods are based on the diffraction of a collimated beam of monochromatic x-rays that is scattered by atoms in a crystal lattice. The Bragg law

$$\lambda = 2d(hk\ell)\sin\theta \tag{22}$$

gives the condition for constructive reflection of the incident radiation. Here d is the separation of the lattice planes, h, k, and ℓ are the Miller indices for the planes, and θ is the angle measured between the direction of the incident or reflected beam and the planes. Except for a small correction due to refraction, the measurement of expansion is independent of wavelength such that

$$\frac{\Delta d(hk\ell)}{d(hk\ell)} = -\cos\theta\ \Delta\theta = \frac{\sin\theta_1 - \sin\theta_2}{\sin\theta_2} \tag{23}$$

where θ_1 and θ_2 are the angles of incidence of the beam with the crystal plane at temperatures T_1 and T_2, respectively.

The relationship between the separation of lattice planes and the symmetry of the crystal lattice is given by

$$\begin{aligned} d^2 = {} & [1 - \cos^2\alpha - \cos^2\beta - \cos^2\gamma + 2\cos\alpha\cos\beta\cos\gamma]/[(h/a)^2\sin^2\alpha \\ & + (k/b)^2\sin^2\beta + (l/c)^2\sin^2\gamma + \frac{2hk}{ab} \times (\cos\alpha\cos\beta - \cos\gamma) \\ & + \frac{2h\ell}{ac}(\cos\alpha\cos\gamma - \cos\beta) + \frac{2k\ell}{bc}(\cos\beta\cos\gamma - \cos\alpha)] \end{aligned} \tag{24}$$

where a, b, and c are lattice spacings and α, β, and γ are the angles between lattice axis b-c, c-a, and a-b, respectively. Using this equation, it can be shown that for a cubic crystal (where a=b=c and $\alpha=\beta=\gamma=90°$) such as NaCl, the expansion can be obtained from any set of lattice planes $(hk\ell)$, e.g.,

$$\frac{\Delta a}{a} = \frac{\Delta d(hk\ell)}{d(hk\ell)} = -\cot\theta\ \Delta\theta \tag{25}$$

The thermal expansion of crystalline materials can be accurately measured with x-ray cameras and diffractometers under conditions that preclude the use of any other method, as when the specimens are very small, weak, and/or irregular in shape. These methods are also unique in that they can easily be used to determine the principal coefficients of thermal expansion of anisotropic crystals and permit direct observation of phase changes. There is a further advantage in that measurements with x-rays do not include effects that are observed in measurements on bulk specimens. The problems associated with heating the specimen and accurately measuring its temperature in both x-ray cameras and diffractometers are discussed in several articles [9,22,24].

Unique x-ray techniques exist for special situations. In particular, the use of the Bond technique for single crystals [23] has resulted in a sensitivity of 10^{-7} in measurements of $\Delta a/a$ [1]. In this technique the specimen is rotated between equivalent diffracting orientations on either side of the incident beam. The value of θ thus obtained is unaffected by any specimen eccentricity, absorption, and zero errors, and errors due to specimen title and beam axial divergence are minimized.

The inherent accuracy of this technique is extremely high for well characterized and stable materials.

REFERENCES TO TEXT

1. ASTM, ASTM Standards, Part 41, 1974.
2. Banaev, A.M. and Chekhovskoi, V.Ya., Teplofiz. Vys. Temp., 3(1), 57-63, 1965; English translation: High Temp., 3(1), 47-52, 1965.
3. Schröder, J., Rev. Sci. Instrum., 34, 615-21, 1963.
4. Beck, A.E., J. Sci. Instrum., 34, 186-9, 1957.
5. Beck, A.E., Geophysics, 41, 9-16, 1977.
6. Beck, A.E., Anglin, F.M., and Sass, J.H., Can. J. Earth Sci., 8, 1-19, 1971.
7. Benfield, A.E., Proc. Roy. Soc. London, A173, 428-50, 1939.
8. Birch, F., Geol. Soc. Am. Bull., 61, 597-630, 1950.
9. Brand, J.A. and Goldschmidt, H.J., J. Sci. Instrum., 33, 41-5, 1956.
10. Candler, C., *Modern Interferometers*, The University Press, Glasgow, 502 pp., 1951.
11. Carslaw, H.S. and Jaeger, J.C., *Conduction of Heat in Solids*, Oxford University Press, London, 428 pp., 1959.
12. Clark, S.P., Am. Mineral., 42, 732-42, 1957.
13. Clusener, G.R., in *AIP Conference Proceedings No. 3 - Thermal Expansion*, American Institute of Physics, New York, 51-8, 1972.
14. Dyson, J., *Interferometry as a Measuring Tool*, Hunt Barnard Printing, Ltd., Aylesbury, 206 pp., 1970.
15. Feder, R. and Charbnau, H.P., Phys. Rev., 149, 464-71, 1966.
16. Fraser, D.B. and Hollis-Hallet, A.C., Can. J. Phys., 43, 193-219, 1965.
17. Hanley, E.J., DeWitt, D.P., and Roy, R.F., Eng. Geol. (Amsterdam), 12, 31-47, 1978.
18. d'Heurle, F.M., Feder, R., and Nowick, A.S., J. Phys. Soc. Jpn., 18(Suppl. II), 184-90, 1963.
19. Stiller, H., Vollstadt, H., and Seipold, V., Phys. Earth Planet. Inter., 17, 31-4, 1978.
20. Jaeger, J.C., Aust. J. Phys., 9, 167-79, 1956.
21. Jenkins, F.A. and White, H.E., *Fundamentals of Optics*, McGraw-Hill Book Co., New York, NY, 637 pp., 1957.
22. Mauer, F.A. and Bolz, L.H., *Advances in X-Ray Analysis* (Mueller, W.M., Editor), Vol. 5, Plenum Press, New York, NY, 546 pp., 1961.
23. Mauer, F.A. and Hahn, T.A., in *AIP Conference Proceedings No. 3 - Thermal Expansion*, American Institute of Physics, New York, 139-50, 1972.
24. Merryman, R.G. and Kempter, C.P., J. Am. Ceram. Soc., 48, 202-5, 1965.
25. Parker, W.J., Jenkins, R.J., Butler, C.P., and Abbott, G.L., J. Appl. Phys., 32, 1679-84, 1961.

26. Plummer, W.A., in AIP Conference Proceedings No. 3 - Thermal Expansion, American Institute of Physics, New York, 36-43, 1972.

27. Plummer, W.A., in AIP Conference Proceedings No. 17 - Thermal Expansion, American Institute of Physics, New York, 147-8, 1974.

28. Taylor, R.E. and Clark, L.M., High Temp.-High Pressures, 6, 65-72, 1974.

29. von Herzen, R.P. and Maxwell, A.E., J. Geophys. Res., 64, 1557-63, 1959.

30. Saunders, J.B., J. Res. Natl. Bur. Stand., 35, 157-86, 1945.

31. Woodside, W. and Messmer, J.H., J. Appl. Phys., 32, 1688-99 (Part 1); 1699-706 (Part 2), 1961.

EXAMPLES OF NUMERICAL DATA

In this part of the report, illustrative data are given for four thermophysical properties of basalt, granite, shale, and tuff as a function of temperature. In a number of cases, specific comments pertaining to the applicability of the data are made on the figures or in the captions to each figure but, in general, the following points should be borne in mind when interpreting the data and putting them to a particular use.

Rocks are classified broadly in terms of their mineralogical and structural characteristics. Within a particular rock type there may be a sufficient variation of these characteristics to give very different thermal properties; for example, in granite the thermal conductivity value depends quite strongly upon the quartz content but, nevertheless, other factors may have a strong influence, producing much scatter about a linear trend when quartz content is plotted against conductivity.

For porous rocks, the thermal conductivity may be strongly dependent upon the conductivity of the pore fluid; as indicated in an earlier section, it may sometimes be necessary to calculate thermal conductivity from a knowledge of the rock matrix, porosity, and nature of the pore fluid. However, it is most important that the thermal conductivity of the matrix material be accurately known. Among the various parameters influencing the thermal properties of rocks, porosity is perhaps the most important. Because of this, much of the original literature data has been rejected because the data on conductivity values are given with no reference to the porosity of the rocks.

In trying to estimate the probable variation of a thermal property with temperature (or pressure), the room temperature value in the appropriate figure should first be located and an interpolated curve drawn roughly parallel to the ones shown for a specific case with a possibly different starting room temperature value.

In reviewing the vast amount of data in the literature, one finds that many of the frequently quoted sources are, in fact, secondary sources which, upon investigation, sometimes differ from the original source both in magnitude of the property values as well as interpretation. Wherever possible, the original sources have been consulted. Except for a limited number of specific cases, it has not been possible to recommend temperature dependent property values due to the extreme scatter in the data and the lack of adequate specimen characterization. Hence, it was decided to report a band, or a range of probable values, a property can assume based on the various parameters discussed above. An extensive bibliography is presented with the data figures for those interested in recreating the topography of the original data for a given property.

Upon careful examination of the literature data on the thermophysical properties covered in this Section, it became clear that the literature, while reasonably abundant in data, is most inadequate for the proper selection and recommendation of reliable design data. Hence, it became necessary to discard large numbers of data references and to be satisfied by the simple indications of upper and lower bounds within which the data may fall based on rock composition, structure, porosity, water content, etc. These factors often influence the variation of the property more than such variables as temperature and pressure. Whenever adequate data were available, histograms were constructed for the room temperature thermal conductivity of certain rock systems.

Sight-specific data are nearly non-existent for well characterized rocks for either in-situ or laboratory measurements. The need for new data, in nearly all areas, cannot be stressed strongly enough for well characterized specimens.

On pages 19 through 23 illustrative examples of data are given in Figures 1 through 10.

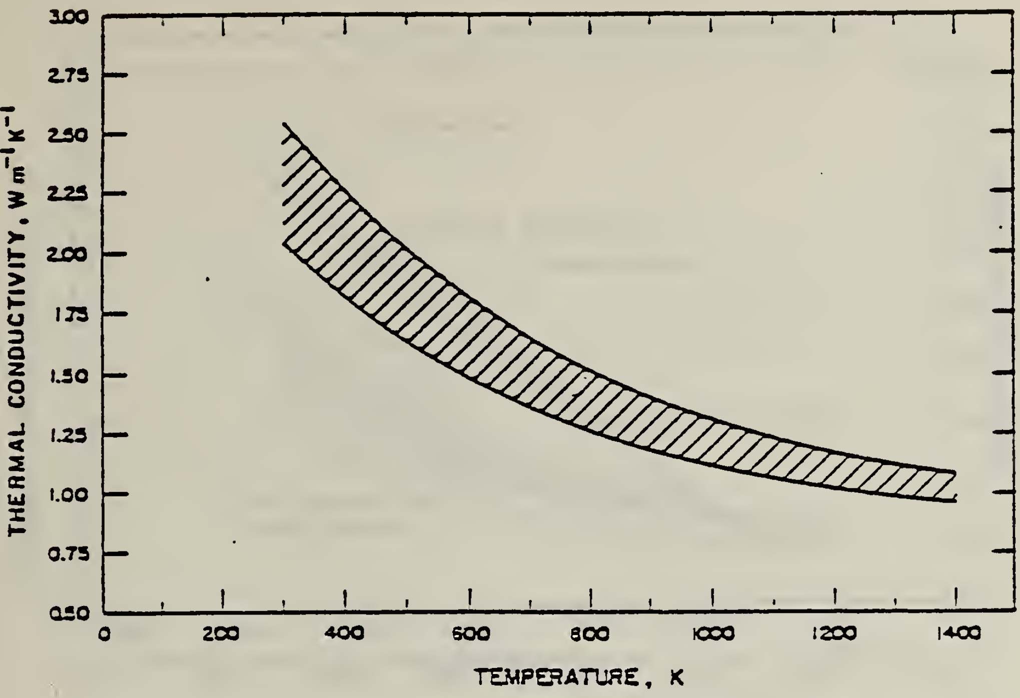


FIGURE 1. THERMAL CONDUCTIVITY OF BASALT.

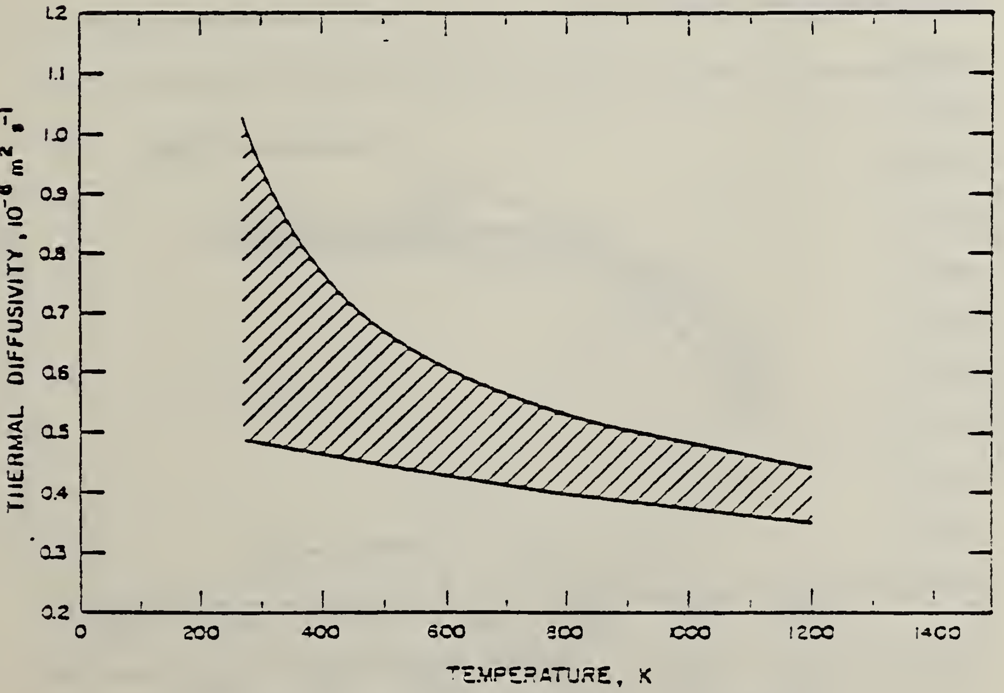


FIGURE 2. THERMAL DIFFUSIVITY OF BASALT.

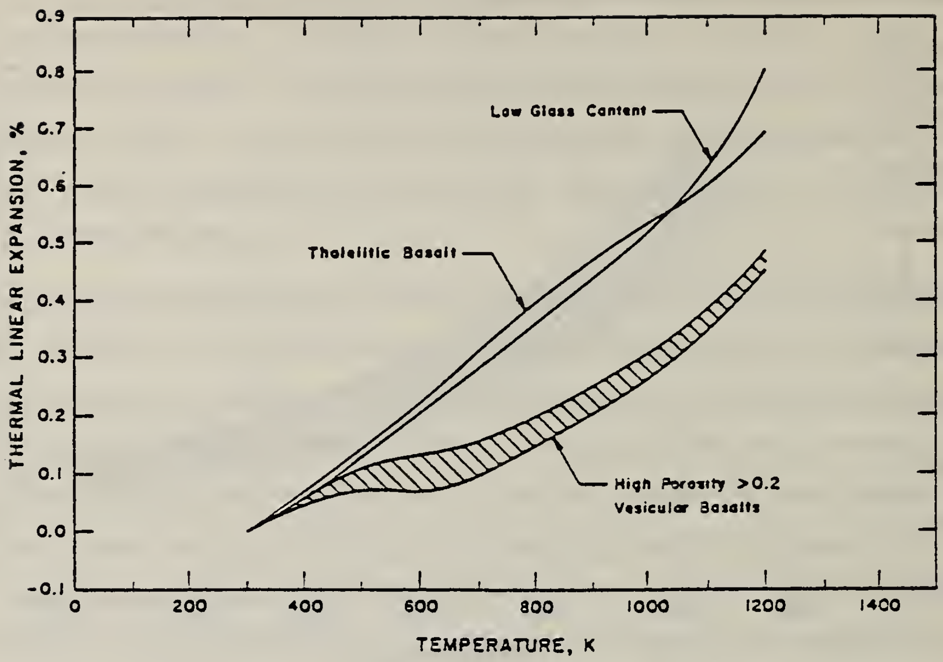


FIGURE 3. THERMAL LINEAR EXPANSION OF BASALT [63].

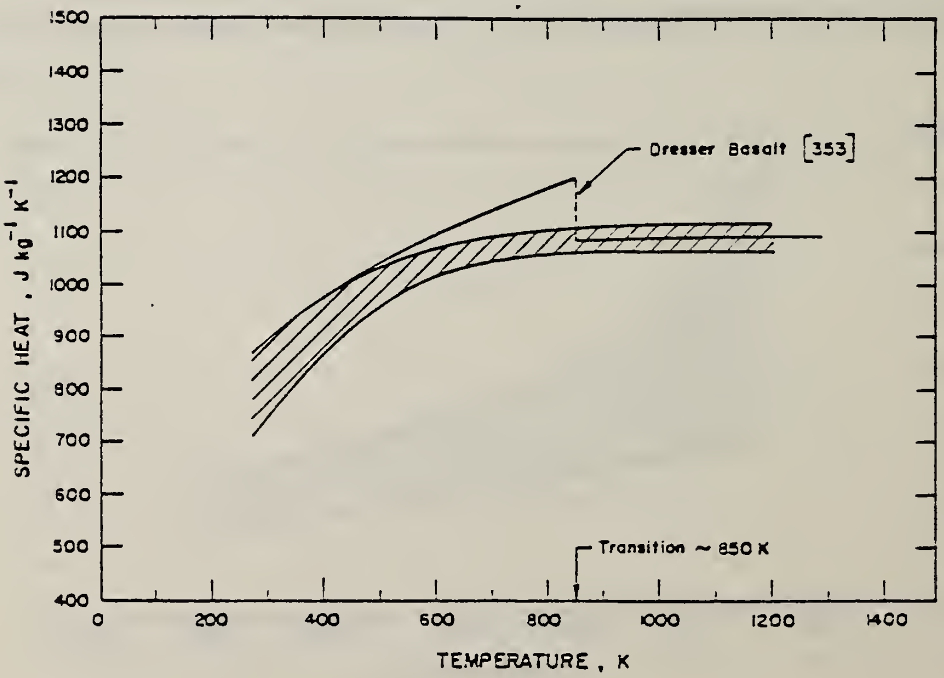


FIGURE 4. SPECIFIC HEAT OF BASALT.

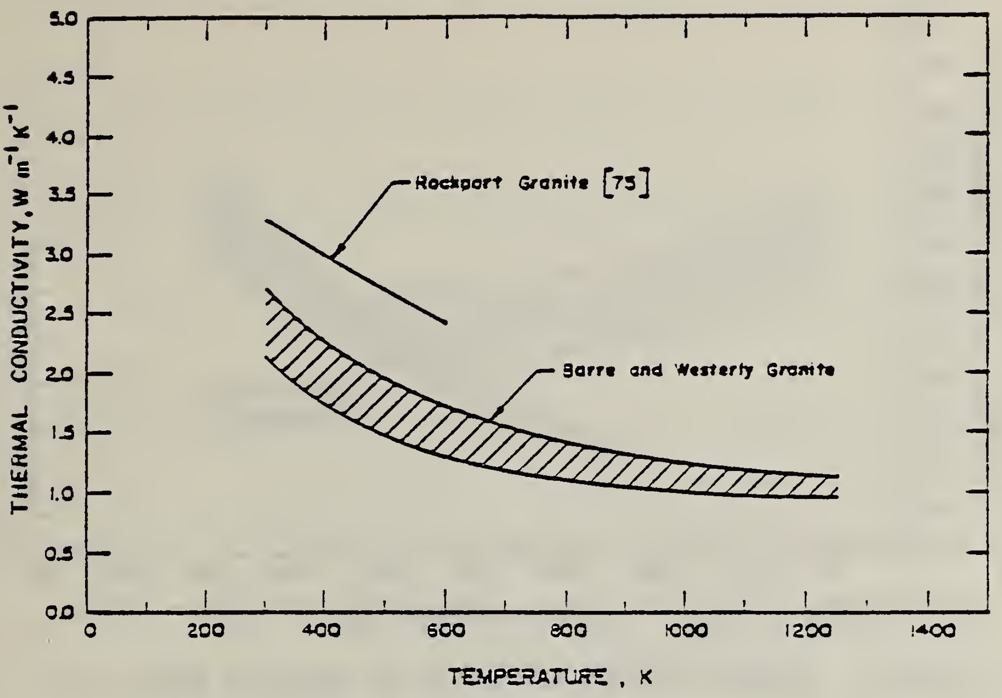


FIGURE 5. THERMAL CONDUCTIVITY OF GRANITE ROCKS.

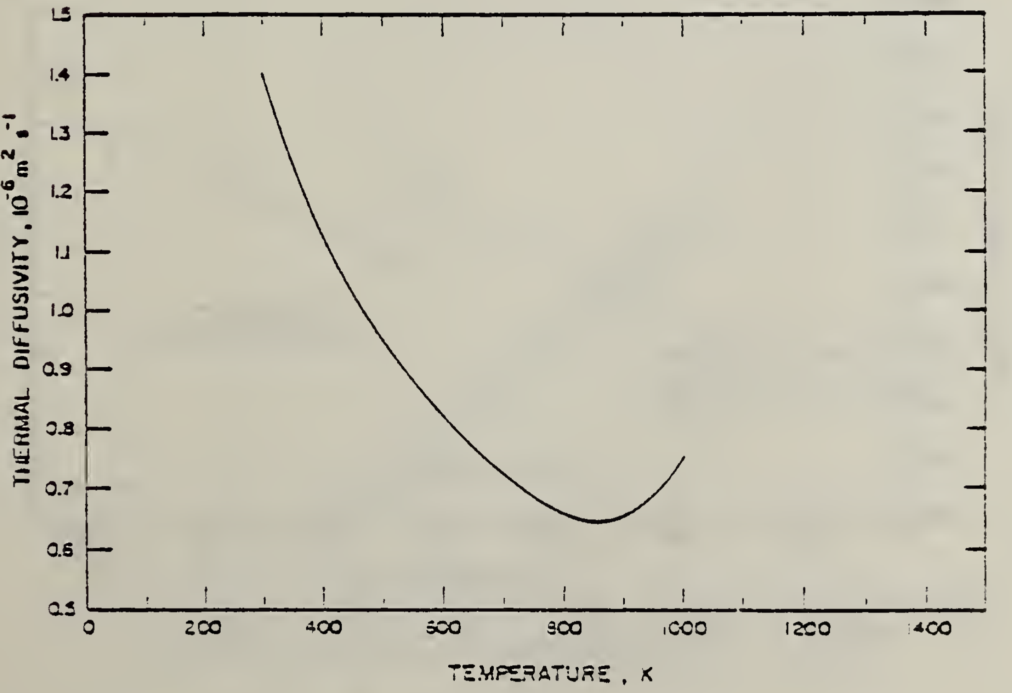


FIGURE 6. THERMAL DIFFUSIVITY OF BARRE AND WESTERLEY GRANITE [39].

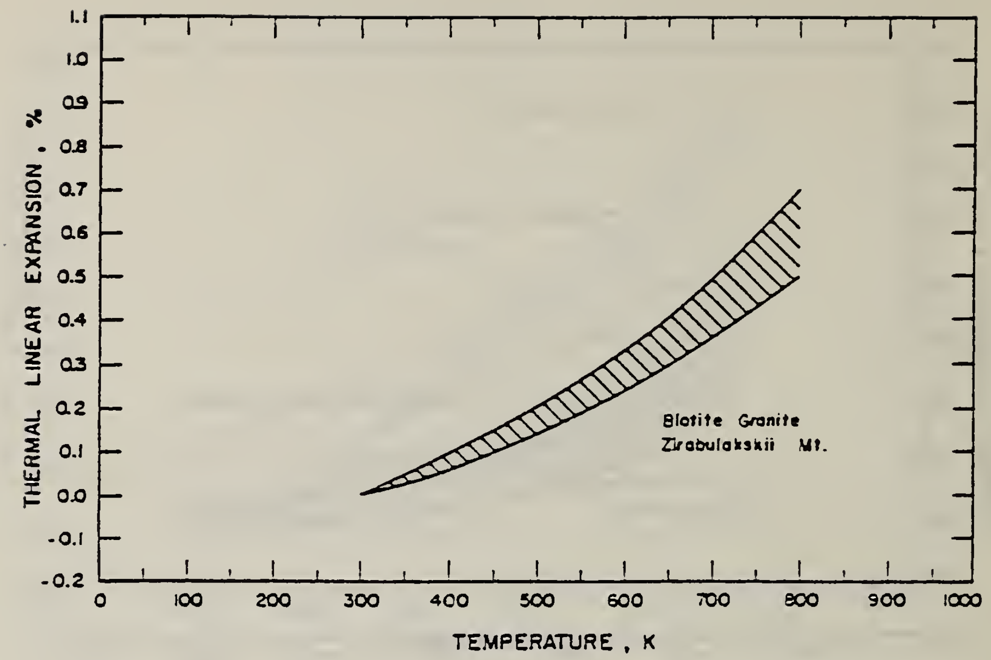


FIGURE 7. THERMAL LINEAR EXPANSION OF GRANITIC ROCKS [45].

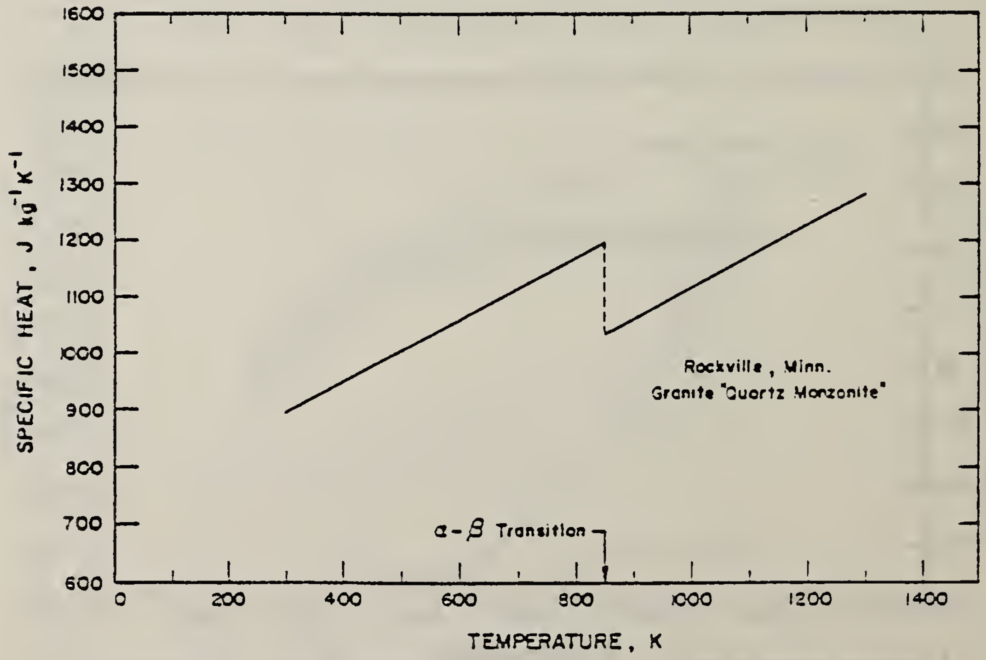


FIGURE 8. SPECIFIC HEAT OF GRANITIC ROCK [59].

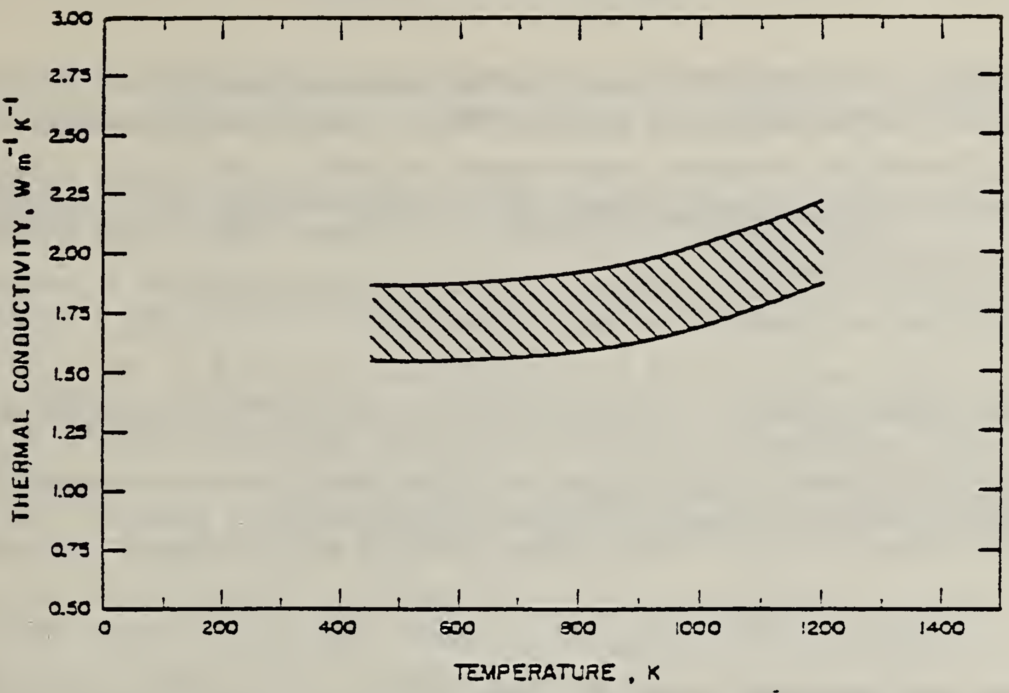


FIGURE 9. THERMAL CONDUCTIVITY OF TUFF [15].

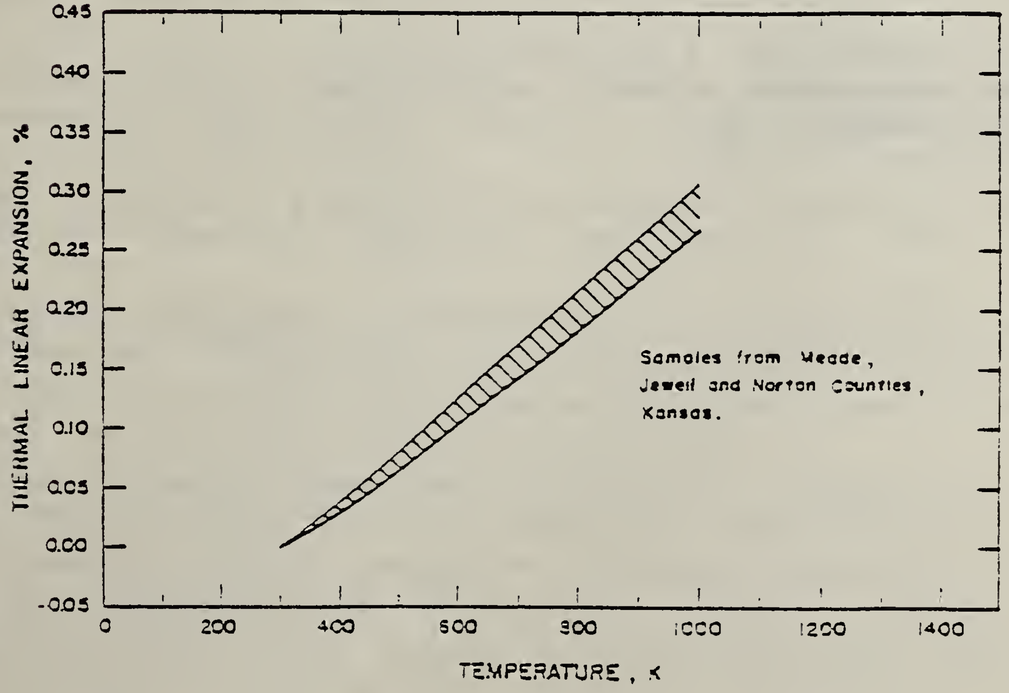


FIGURE 10. THERMAL LINEAR EXPANSION OF TUFF [17].

INDEX TO BIBLIOGRAPHY TO DATA ON THERMOPHYSICAL PROPERTIES OF BASALT, GRANITE, AND TUFF

References cited here contain data which were used as the basis for the figures presented in this report. While the presentation of the data is generally from room temperature to 1500 K, the listed references cite data below and above these temperature limits. Refer to the Bibliography for the reference citations.

Basalt

Thermal conductivity: 8,12,15,17,18,19,21,22,23,24,27,29,30,36,38,39, 40,42,46,53,60,61,64,68,70,74,75,80,82,85,87,90
Thermal diffusivity: 8,11,18,44,48,54,67,68,69,80,81,83,84,85,89
Thermal expansion: 26,32,34,55,56,63,72,73,79,85
Specific heat: 8,11,14,18,19,30,38,49,52,59,68,71,79,85,86

Granite

Thermal conductivity: 2,5,7,8,13,16,19,20,22,28,33,35,43,50,51,62,64, 65,76,77,78,88
Thermal diffusivity: 1,8,13,62,89
Thermal expansion: 25,32,45,55,56,58,66,72,73
Specific heat: 4,8,9,10,13,14,19,31,37,52,57,59,71,77

Tuff

Thermal conductivity: 3,8,15,35,38,41,62,78,87
Thermal diffusivity: 8,41,62
Thermal expansion: 47
Specific heat: 6,8,38,62

BIBLIOGRAPHY TO DATA

1. "Measuring the Thermal Conductivity of Rocks," Petrunin, G.I. and Yurchak, R.P., Izv. Acad. Sci., USSR, Phys. Solid Earth, 11, 749-51, 1973.
2. "A Method for the Determination of the Thermal Conductivity of Rocks," Nancarrow, H.A., Proc. Phys. Soc., London, 45, 447-61, 1933.
3. "Influence of the Concentration of the Coloring Molecules and of the Viscosity of the Solvent on the Decay Time of Fluorescence Radiation,"
4. "Specific Heat of Rocks and the Velocity of Elastic Waves Within the Outer Layer of the Earths Crust," Noritomi, K., Sci. Rep. Tohoku Imp. Univ., 7(5), 190-200, 1956.
5. "On the Measurement of the Thermal Conductivities of Rocks by Observations on a Divided Bar Apparatus," Beck, A.E. and Beck, J.M., Trans. Am. Geophys. Union, 39(6), 1111-23, 1958.
6. "Coefficients of Transfer of Heat by Tuffaceous Stones," Gindoyan, A.G., Izv. Akad. Nauk Arm. SSR Ser. Tekh. Nauk, 13(2), 29-42, 1960.
7. "The Thermal Conductivity of Rocks and its Dependence Upon Temperature and Composition," Birch, F. and Clark, H., Am. J. Sci., 238, 529-58, 1940.
8. "The Determination of the Thermal Conductivity, Specific Heat, Density and Thermal Expansion of Different Rocks and Refractory Materials," Tadokoro, Y., Sci. Rep. Tohoku Imp. Univ., 10, 339-410, 1921.
9. "Measuring the Values of the Specific Heats of Materials Used in Construction," Pascal, M.A., Ann. Inst. Tech. Batiment et Trav. Publ., 7(77), 372-85, 1954.
10. "The Uses of Complete Temperature-Time Curves for Determination of Thermal Conductivity with Particular Reference to Rocks," Jaeger, J.C., Aust. J. Phys., 12(3), 203-17, 1959.
11. "Thermal Properties of a Simulated Lunar Material in Air and in Vacuum," Bernett, E.C., Wood, H.L., Jaffe, L.D., and Martens, H.E., AIAA J., 1(6), 1402-7, 1963.
12. "The Thermal Conductivity and Compressibility of Several Rocks Under High Pressures," Bridgman, P.W., Am. J. Sci., 7(9), 81-102, 1924.
13. "Heat Conductivity Data for Some Scandinavian Natural Stones," Lorentzen. G., Bull. Inst. Int. Froid Annexe 2, 45-53, 1964.
14. "Non-Metallic Thermal Storage Media," Svikis, V.D., Canadian Dept. of Mines Tech. Surv. Mines Branch Res. Rept. R-96, 42 pp., 1962.
15. "High Temperature Thermal Conductivity of Six Rocks," Stephens, D.R., USAEC Rept. UCRL-7605, 19 pp., 1963.
16. "Heat Flow in South Africa," Bullard, E.C., Proc. Roy. Soc. London, 173A, 474-502, 1939.
17. "Thermodynamic Calculations for Rocket Engines," Nikolaev, B.A., U.S. Army Rept. FTD-TT-62-271, 193 pp., 1962. [AD 277 653]

18. "Thermal Properties of Simulated Lunar Material in Air and in Vacuum," Bernett, E.C., Wood, H.L., Jaffe, L.D., and Martens, H.E., California Institute of Technology, Jet Propulsion Laboratory Rept. JPL-TR-32-368, 19 pp., 1962.

19. "On the Thermal Conductivity and Specific Heat of Granite and Basalt at High Temperatures." Poole, H.H., Phil. Mag., 27, 58-83, 1914.

20. "Heat Flow in the Transvaal and Orange Free State," Carte, A.E., Proc. Phys. Soc. London, 67B, 664-72, 1954.

21. "Studies of the Physical Characteristics of Probable Lunar Surface Materials. Part II. Final Rept., Pt. 2 for Oct., 1963 - Oct., 1964 " Glaser, P.E., U.S. Air Force Rept. AFCRL-64-970 (Pt. 2), 134 pp., 1964. [AD 613 965]

22. "Thermal Conductivity of Rock. Measurement by the Transient Line Source Method," Marovelli, R.L. and Veith, K.F., Bureau of Mines Rept. BM-RI-6604, 19 pp., 1965.

23. "Thermal Conductivity of Lunar and Terrestrial Igneous Rocks in Their Melting Range," Murase, T. and McBirney, A.R., Science, 170, 165-7, 1970.

24. "Low-Temperature Heat Capacity of Liquid HE-3, Abel, W.R., Anderson, A.C., Black, W.C., and Wheatley, J.C., Phys. Rev. Lett., 15(23), 875-8, 1965.

25. "Thermal Volume Change and Elasticity of Aggregates and Their Effect on Concrete," Willis, T.F. and DeReus, M.E., Proc. Am. Soc. Test. Mater., 39, 919-28, 1939.

26. "Compressibilities and Electrical Resistance Under Pressure, with Special Reference to Intermetallic Compounds," Bridgman, P.W., Proc. Am. Acad. Arts Sci., 70(7), 285-317, 1936.

27. "Thermal Properties of a Simulated Lunar Material in Air and in Vacuum," Bernett, E.C., Wood, H.L., Jaffe, L.D., and Martens, H.E., California Institute of Technology, Jet Propulsion Laboratory Rept. JPL-TR-32-369, 23 pp., 1962.

28. "Computing Thermal Conductivities of Rocks from Chips and Conventional Specimens," Beck, J.M. and Beck, A.E., J. Geophys. Res., 70(20), 5227-39, 1965.

29. "Automatic Apparatus with Square Plate Heater for Determination of the Thermal Conductivity of Insulating Materials Used up to 1000°," Ferro, v. and Sacchi, A., Calore, 37(4), 135-49, 1966.

30. "Thermal Properties of Postulated Lunar Surface Materials," Glaser, P.E., Wechsler, A.E., and Germeles, A.E., Ann. N.Y. Acad. Sci., 123(2), 856-70, 1965.

31. "Application of Thermodynamic Calculations to Geochemistry, and New Data on the Heat Capacities of Quartz, Kyanite, and Granite," Leonidov, V.Y., Geokhim. Issled. Obt. Povyshennykh Davlenii Temp., Adad. Nauk SSSR Inst. Geokhim. Anal. Khim. Sb. Stat., 191-202, 1965.

32. "Thermal Expansion Tests on Aggregates, Neat Cements, and Concretes," Mitchell, L.J., Am. Soc. Test. Mater. Proc., 53, 963-75, 1953.

33. "Thermal Conductivity of Rocks by a Ring Source Device," Mossahebi, M., Univ. of California, Berkeley, M.S. Thesis, 77 pp., 1966.

34. "Investigating Daubabinsk Tephrite Basalts for Making Stone Castings," Suleimenov, S.T., Abduvaliev, T.A., Sharafiev, M.S., and Tropina, L.G., Glass Ceram. USSR (Engl. Transl.), 23(4), 192-5, 1966.

35. "The Measurement of the Flow of Heat Through the Crust of the Earth and Through Rocks," Beck, A.E., Australian National Univ., Canberra, Ph.D. Thesis, 236 pp., 1956.

36. "Heat-Flow Values from the Precambrian Shield of Western Australia," Sass, J.H., J. Geophys. Res., 69(2), 299-308, 1964.

37. "Temperature Field in Multilayer Systems with Variable Thermal Properties," Meerovich, I.G., Inzh.-Fiz. Zh., 12(4), 484-90, 1967.

38. "Pressure Effects on Postulated Lunar Materials. From Proceedings of the 4th Conference on Thermal Conductivity, San Francisco, California," Wechsler, A.E. and Glaser, P.E., U.S. Naval Radiological Defense Laboratory Rept. USNRDL-TR-4, 31 pp., 1964.

39. "Thermal Conductivity and Dielectric Constant of Silicate Materials," Wechsler, A.E. and Simon, I., NASA Rept. NASA-CR-61495, 133 pp., 1966.

40. "A Line Heat Source Method for the Determination of Thermal Conductivity of Powders in Vacuum," Wechsler, A.E. and Glaser, P.E., in Proceedings of the 3rd Conference on Thermal Conductivity, Oak Ridge National Laboratory, 631-27, 1963.

41. "Thermal Characteristics of Porous Rocks at Elevated Temperatures," Somerton, W.H. and Boozer, G.D., J. Petrol. Technol., 12, 77-81, 1960.

42. "An Automatic Plate Apparatus for Measurements of Thermal Conductivity of Insulating Materials at High Temperatures," Ferro, V. and Sacchi, A., in Proceedings of the Eight Conference on Thermal Conductivity, Plenum Press, New York, NY, 737-60, 1969.

43. "Effect of Pressure and Saturating Fluid on the Thermal Conductivity of Compact Rock," Walsh, J.B. and Decker, E.R., J. Geophys. Res., 71(12), 3053-61, 1966.

44. "Thermal and Dielectric Properties of a Homogeneous Moon Based on Microwave and Infrared Temperature Observations," Calvert, T.A., NASA Rept. NASA-TM-X-1734, 43 pp., 1969.

45. "Thermal Expansion of Rocks and Minerals," Iskandarov, E., Uzb. Geol. Zh., 12(4), 22-5, 1968.

46. "Proton Bombardment-Induced Target Temperatures and Thermal Accomodation Coefficients of Rock Powders," Nash, D.B., NASA Rept. NASA-CR-100922, 22 pp., 1969.

47. "Thermal Expansion of Kansas Volcanic Ash," Bauleke, M.P. and Hugh, J.M., State Geol. Surv. Kans. Bull. No. 194, Pt. 1, 15-16, 1969.

48. "Thermal Diffusivity Measurement," Kanamori, H., Mizutani, H., and Fujii, N., J. Phys. Earth, 17(1), 43-53, 1969.

49. "Specific Heats of Lunar Surface Materials from 90 to 350 K," Robie, R.A., Hemingway, B., and Wilson, W.H., Science, 167, 749-50, 1970.

50. "Effects of Temperature and Pressure on Some Physical Properties of Rocks," Moiseenko, U.I., Istomin, V.E., and Alieva, M.A., Fiz.-Mekh. Svoistva Gorn. Porod Verkh. Chasti Zemnoi Kory, Dokl. Simp. (1964), 148-52, 1968.

51. "Thermal Conductivity and Electrical Conductivity of Rocks at a High Temperature," Moiseenko, U.I., Teplofiz. Svoistva Tverd. Tel. Vys. Temp. Tr. Vses. Konf. (1966), 1, 299-302, 1969.

52. "Nonmetallic Thermal Storage Media for Block-Type Electric Space Heaters," Svikis, V.D., Can., Mines Br., Res. Rept. R206, 44 pp., 1969.

53. "Thermal Conductivity of Particulate Basalt as a Function of Density in Simulated Lunar and Martian Environments," Fountain, J.A. and West, E.A., J. Geophys. Res., 75, 4063-9, 1970.

54. "Properties of Molten Ceramics," Bates, J.L., McNeilly, C.E., and Rasmussen, J.J., Pacific Northwest Lab., Battelle-Northwest Rept. BNWL-SA-3579, 18 pp., 1970.

55. "Thermal Expansion of Concrete Aggregate Materials," Johnson, W.H. and Parsons, W.H., J. Res. Natl. Bur. Stand., 32, 101-26, 1944.

56. "Dilatometer Method for Determination of Thermal Coefficient of Expansion of Fine and Coarse Aggregate," Verbeck, G.J. and Hass, W.E., Highw. Res. Board Proc. Ann. Meet., 30, 187-93, 1951.

57. "Laboratory Research for the Determination of the Thermal Properties of Soils," Kersten, M.S., Univ. of Minnesota, Engineering Experiment Station Rept. CRREL-TR-23, 227 pp., 1949. [AD 712 516]

58. "Phase Composition of Pore Water in Cold Rocks," Mellor, M., Cold Regions Research and Engineering Lab. Rept. CRREL-RR-292, 62 pp., 1970. [AD 719 236]

59. "Heat Content and Specific Heat of Six Rock Types at Temperatures to 1000 C," Lindroth, D.P. and Krawza, W.G., Bureau of Mines Rept. BMRI-7503, 28 pp., 1971. [PB-199046]

60. "Heat Transfer by Radiation and Conduction in Evacuated Powders," Wechsler, A.E., Progr. Refrig. Sci. Technol., Proc. Int. Congr. Refrig., 12th, 2, 267-78, 1969.

61. "Thermal Conductivity Cell for Small Powdered Samples," Cremers, C.J., Rev. Sci. Instrum., 42(11), 1694-6, 1971.

62. "Electric and Thermal Properties of Rocks," Moiseyenko, U.I., Sokolova, L.S., and Istomin, V.Y., NASA Rept. NASA-TT-F-671, 59 pp., 1972.

63. "Thermal Expansion Measurements of Simulated Lunar Rocks," Griffin, R.E. and Demou, S.G., AIP Conf. Proc., 3, 302-11, 1972.

64. "Thermal Conductivity of Nineteen Igneous Rocks. I. Application of the Needle Probe Method to the Measurement of the Thermal Conductivity of Rock," Horai, K. and Baldridge, S., Phys. Earth Planet. Interiors, 5(2), 151-6, 1972.

65. "Thermal Conductivity of Nineteen Igneous Rocks. II. Estimation of the Thermal Conductivity of Rock from the Mineral and Chemical Compositions," Horai, K. and Baldridge, S., Phys. Earth Planet. Interiors, 5(2), 157-66, 1972.

66. "Apparatus for Determining the Coefficient of Thermal Expansion of Rocks, Mortars, and Concretes," Loubser, P.J. and Bryden, J.G., Mag. Concr. Res., 24(79), 97-100, 1972.

67. "Temperature Conductivity of Basalts at Temperatures from 300 to 1200 K," Petrunin, G.I., Yurchak, R.I., and Tkach, G.F., Izv. Akad. Nauk SSSR, Fiz. Zemli, 2, 65-8, 1978; Engl. Transl.: Bull. Acad. Sci., USSR, Earth Phys., 2, 126-7, 1971.

68. "Investigation of the Thermal Properties of Lunar Soil and of its Terrestial Analogs," Dimitriev, A.P., Dukhovskoi, E.A., Novik, G.Y., and Petrochenkov, R.G., Dokl. Akad. Nauk, SSSR, 199(5), 1036-7, 1971; Engl. transl.: Sov. Phys.-Dokl.

69. "Thermal Diffusivity of Lunar Rocks Under Atmospheric and Vacuum Conditions," Fujii, N. and Osako, M., Earth Planet. Sci. Lett., 18(1), 65-71, 1973.

70. "Determination of Rock Thermal Properties," Bacon, J.F., Russell, S., and Carstens, J.P., United Aircraft Research Labs. Rept. UARL-L911397-4, 56 pp., 1973. [AD 755 218]

71. "Heat Capacities of Rocks at High Temperatures," Leonidov, V.Y., Geokhimiya, 4, 470-2, 1967; Engl. transl.: Geochemistry, 4, 400-2, 1967.

72. "Thermal Expansion of Insulating Materials," Souder, W.H. and Hidnert, P., J. Res. Natl. Bur. Stand., 15, 387-417, 1919.

73. "Thermal and Moisture Expansion Studies of Some Domestic Granites," Hockman, A. and Kessler, D.W., J. Res. Natl. Bur. Stand., 44, 395-410, 1950.

74. "Thermal Conductivity of Particulate Materials: A Summary of Measurements taken at the Marshall Space Flight Center," Fountain, J.A., NASA Rept. NASA-TM-X-64759, 72 pp., 1973.

75. "A Comparison of Thermal Conductivity with Elastic Properties for Six Igneous Rock Types," Johnson, S.A., Purdue Univ., M.S. Thesis, 104 pp., 1974.

76. "Analysis of Heat Flow Data in Situ Thermal Conductivity Measurements," Beck, A.E., Anglin, F.M., and Sass, J.H., Can. J. Earth Sci., 8, (1), 1-19, 1971.

77. "The Thermal Properties of Rocks in a Temperature Field," Dmitriev, A.P., Derbenev, L.S., and Goncharov, S.A., Fiz. Tekh. Probl. Razrab. Polez. Iskop., 2, 107-8, 1969; Engl. Transl.: Sov. Min. Sci., 2, 199-200, 1969.

78. "Thermal Conductivity of Rocks from Measurements on Fragments and its Application to Heat Flow Determinations," Sass, J.H., Lachenbruch, A.H., and Munroe, R.J., J. Geophys. Res., 76(14), 3391-401, 1971.

79. "Amorphous Semiconductor Films as Window Coatings for High Energy Lasers," Donovan, T.M. and Knotek, M.L., U.S. Air Force Rept. AFCRL-SR-162-Vol. 2, 821-8, 1972. [AD 914 501L]

80. "Thermal Rock Breaker for Hard Rock Crushing - A Feasibility Study," Thirumalai, K., Chueung, J.B., Chen, T.S., Demou. S.G., and Krawza, W.G., 272 pp., 1972. [AD 916 785L]

81. "Thermal Diffusivity of Six Igneous Rocks at Elevated Temperatures and Reduced Pressures," Lindroth, D.P., Bureau of Mines Rept. Invest. BM-RI-7954, 38 pp., 1974.

82. "The Physical Properties of Oceanic Basement Rocks from Deep Drilling on the Mid-Atlantic Ridge," Hyndman, R.D. and Drury, M.J., J. Geophys. Res., 81(23), 4042-52, 1976.

83. "Thermal Diffusivity of Four Apollo 17 Rock Samples," Horai, K. and Winkler, J., Jr., Proc. Lunar Sci. Conf., 7th, 3183-204, 1976.

84. "Physical Properties of Mohole Test Site Basalt," Somerton, W.H., Ward, S.H., and King, M.S., J. Geophys. Res., 68(3), 849-56, 1963.

85. "Selected Physicochemical Properties of Basaltic Rocks, Liquids, and Glasses," Krupka, M.C., Los Alamos Scientific Lab. Rept. LA-5540, 11 pp., 1974.

86. "Specific Heat of Some Rocks at High Temperatures," Leonidov, V.Y., Geokhimiya, 4, 470-2, 1967.

87. "Basic Heat Flow Data from the United States," Sass, J.H. and Munroe, R.J., (Editors), U.S. Geological Survey Open File Rept. 74-9, Sects. 2-7, 1974.

88. "Basic Data for Some Recent Australian Heat Flow Measurements," Munroe, R.J., Sass, J.H., Milburn, G.T., Jaeger, J.C., and Tammemagi, H.Y., U.S. Geological Survey Open File Rept. 75-567, 1975.

89. "The Thermal Diffusivity of Eight Well-Characterized Rocks for the Temperature Range 300-1000 K," Hanley, E.J., DeWitt, D.P., and Roy, R.F., Eng. Geol., 12, 31-47, 1978.

90. "Thermal Conductivity of Vesicular Basalt from Hawaii," Robertson, E.C. and Peck, D.L., J. Geophys. Res., 79(32), 4875-88, 1974.

PART II. ELECTRICAL CONDUCTIVITY OF BASALT, GRANITE, SHALE, AND TUFF

DEFINITIONS

Rocks are generally electrical nonconductors. However, under this category it may be useful to define three classes of materials; namely:

Nonconductor: A material in which there are energy barriers between the atoms and where electrons are tightly trapped near atoms. Electrical conductivity increases with increasing temperature as thermal activity overcomes the energy barriers. This broad group of materials can be further sub-classified as:

a) *Insulators*: Materials with very large energy barriers between atoms such that electrons generally are not the charge transport carriers. At elevated temperatures charge is carried by ionic conduction through the movement of entire atoms within the material. At lower temperatures, charge transport is by tunnelling or defect diffusion.

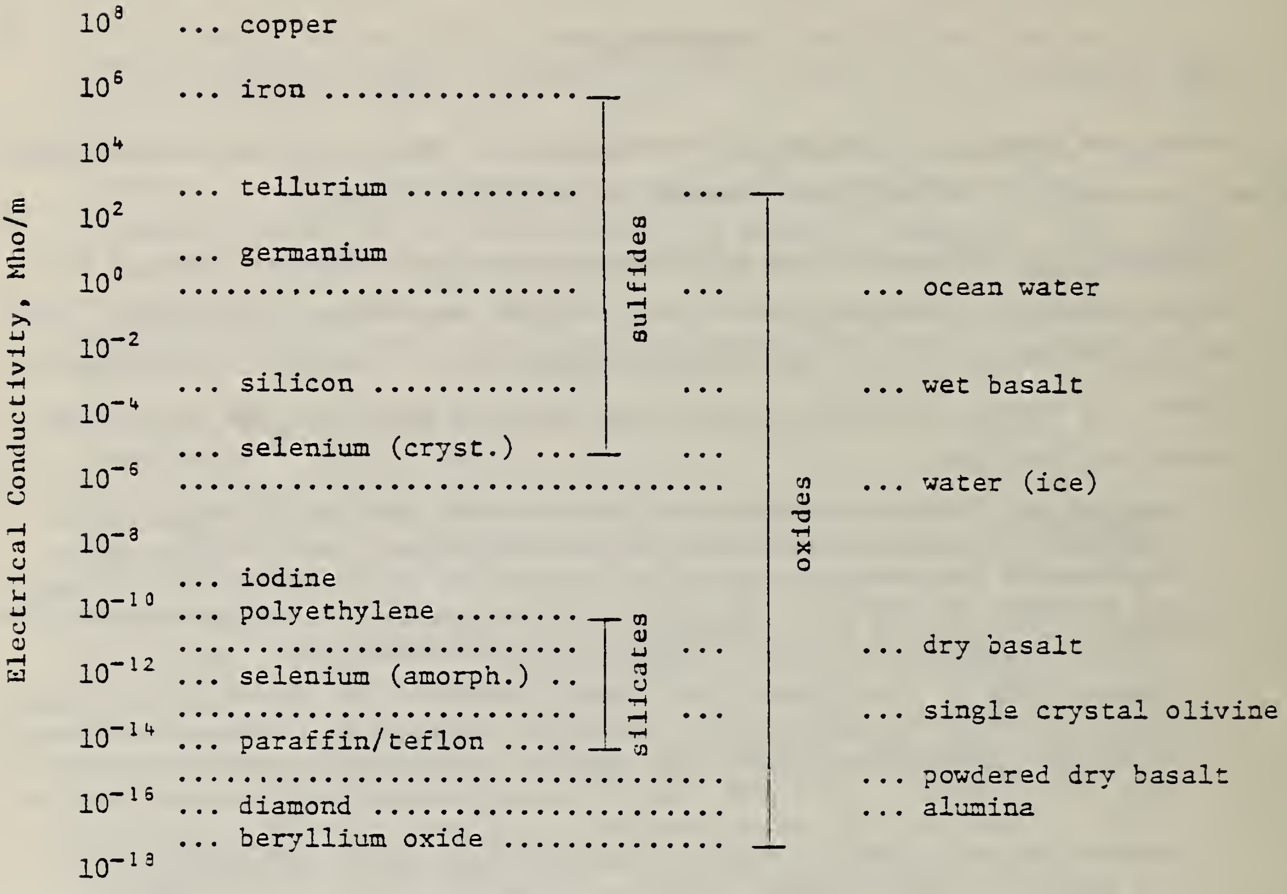
b) *Semiconductors*: Materials with energy barriers that are slightly higher than the available energy from thermal activation at room temperature. At higher temperatures, electrons may be sufficiently activated to overcome the barriers. At lower temperatures, charge transport is by electrons or holes moving across barriers that are lowered by impurities within the material. (A hole is the positive charge associated with the absence of an electron or vacancy moving through the material.)

c) *Electrolytes*: Materials which split (dissociate) into oppositely charged particles when dissolved in appropriate solutions. The motion of the charged particles is hindered by the viscosity of the solution and interparticle interactions. Electrical conductivity of these materials in solution generally increases with increasing temperature until near the critical point of the solution where it decreases with further temperature increase.

ELECTRICAL CONDUCTIVITY AND ITS VARIATIONS

Figure 11 illustrates the great range of electrical conductivity found in common materials. As already discussed in the general introduction, most geologic materials have electrical conductivities that are extremely dependent upon the state and content of water in the material. The most important aspects of water in materials involve the void morphology in the total amount of void space available for water and the connectivity of the voids. Secondary aspects include the surface area of the voids and the chemical interactions between the aqueous solution and the material.

FIGURE 11. THE ROOM TEMPERATURE DC ELECTRICAL CONDUCTIVITY OF A VARIETY OF MATERIALS*



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*As the basalt example shows, most materials can have greatly increased conductivities by the addition of water or greatly reduced conductivities by powdering (Reduction of grain-grain contacts).

A number of complications arise in materials that do not obey the linear relationship between current density and electric field, known as Ohm's Law. Olhoeft [14] has discussed some of the implications of such nonlinear behavior, with many examples existing in the literature [1,5,8,9,10,17,18, and others]. In materials which exhibit nonlinear electrical behavior, it is the water-rock chemical interaction, through oxidation-reduction chemistry or cation exchange processes, that cause and determine the observed nonlinearities. Thus, the chemistry of water-rock interactions is very important in determining electrical properties of wet rocks through surface conduction, interfacial polarization, and charge transport by chemical reaction at or across the water-rock boundary. It is because of this last feature that the measurement of the electrical properties of wet rocks is particularly prone to error.

MEASUREMENT OF ELECTRICAL PROPERTIES AND SOURCES OF ERRORS

Before giving examples of electrical properties, let us consider the sources of error in typical measurements. In dry rock measurements, the largest errors are caused by current leakage around the sample (through the sample holder assembly), by cable coupling, by capacitance fringing effects, and by systematic instrument biases. Of these errors, adequate sample measurement system design can eliminate or reduce these effects to a very small fraction of one percent (±0.4% spread worldwide among all standard laboratories) in absolute terms or less than ±0.005% relative. The principle method of accomplishing this is by the use of 3-terminal or 3-electrode sample holders [13,20].

In wet rocks, additional errors occur due to current leakage around the sample via wet surface conduction paths, faradaic charge transfer impedances between the electrodes and the sample, and chemical reaction between sample and sample holder. These error sources can be reduced to a fraction of one percent by using inert materials (platinum and teflon as examples) in a four-terminal shielded sample holder [15]. As these errors are not known as well as the dry system errors, they will be discussed in detail.

Figure 12 illustrates a typical four-terminal cell arrangement. The significant soruces of error are listed and shown in the circuit diagram of Figure 13. Leakage and surface conduction are eliminated by proper sample jacketing (potting or confining pressure sleeve) and sample holder construction. The charge transfer impedance at the current electrodes is not important, as it lies outside the region where potential drop is measured (though it may prove troublesome to the source). The charge transfer impedance at the potential electrodes is minimized by using a very high input impedance measurement circuit so no significant current (picoamperes or less) is drawn through that circuit. The potential electrodes are also not allowed to touch the sample to prevent contact polarizations and related phenomena [13]. Either the potential electrodes are separated from the sample by a thin porous teflon membrane, or by a small distance in the solution, or by a paste of fumed silica gel, all of which add a small error typically less than 0.3% in magnitude and a few milliradians in phase. The capacitative and inductive cable coupling effects are eliminated by using driven shield circuitry and adequate low noise shield

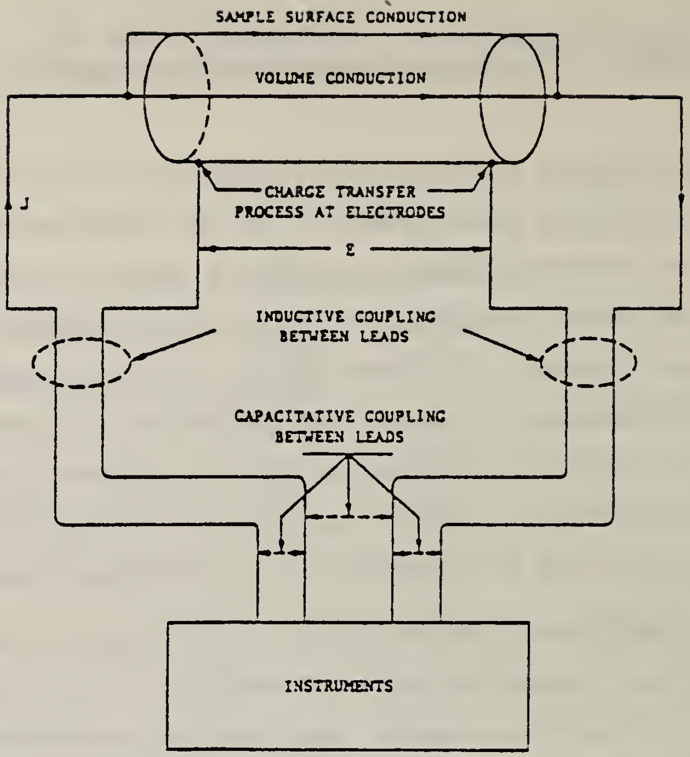

FIGURE 12. TYPICAL FOUR-TERMINAL ARRANGEMENT FOR THE MEASUREMENT OF ELECTRICAL PROPERTIES OF ROCK SAMPLES.

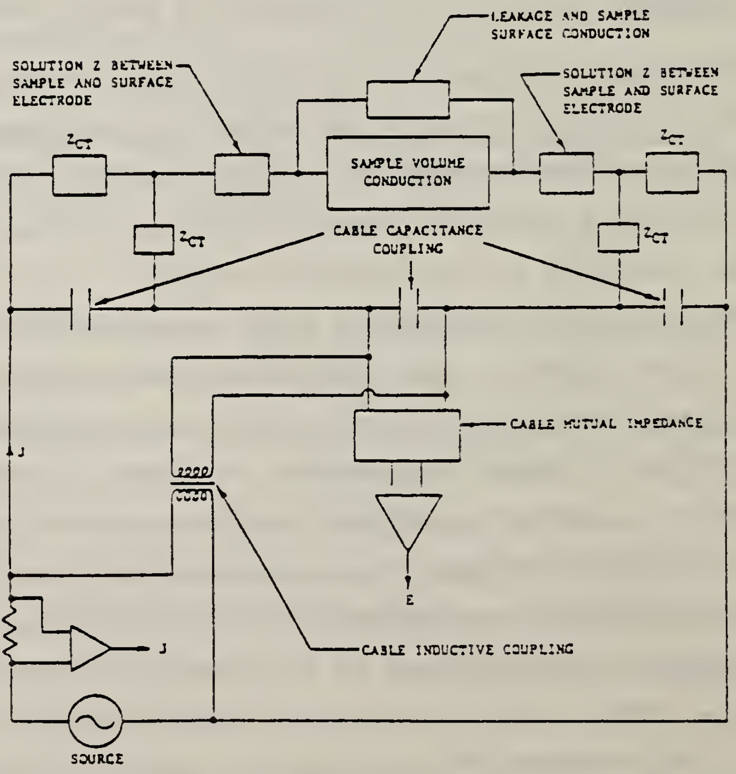

FIGURE 13. ELECTRICAL CIRCUIT DIAGRAM OF THE FOUR-TERMINAL CELL ARRANGEMENT (FIGURE 12) INDICATING THE PRESENCE OF MAJOR SOURCES OF ERROR.

construction techniques. Thus, Figure 14 summarizes the typical 4-electrode sample holder.

Instrumentation and noise errors are still possible (such as source harmonic distortion, receiver Hilbert distortion, etc.), but these errors may be handled by standard statistical techniques and good laboratory practice.

DISCUSSION OF DATA

ELECTRICAL PROPERTIES OF BASALT

Figure 15 [12] illustrates the extreme sensitivity of electrical properties to small amounts of water in silicates such as basalt. The DC electrical conductivity does not begin to change until there is sufficient water in the sample to create a connected path from one electrode to the other in the measurement system (in this case about 0.002 wt.% water or about 20% of a monolayer). The dielectric permittivity and loss tangent, however, do not begin to change significantly until more than a monolayer (about 0.01 wt.%) of water has

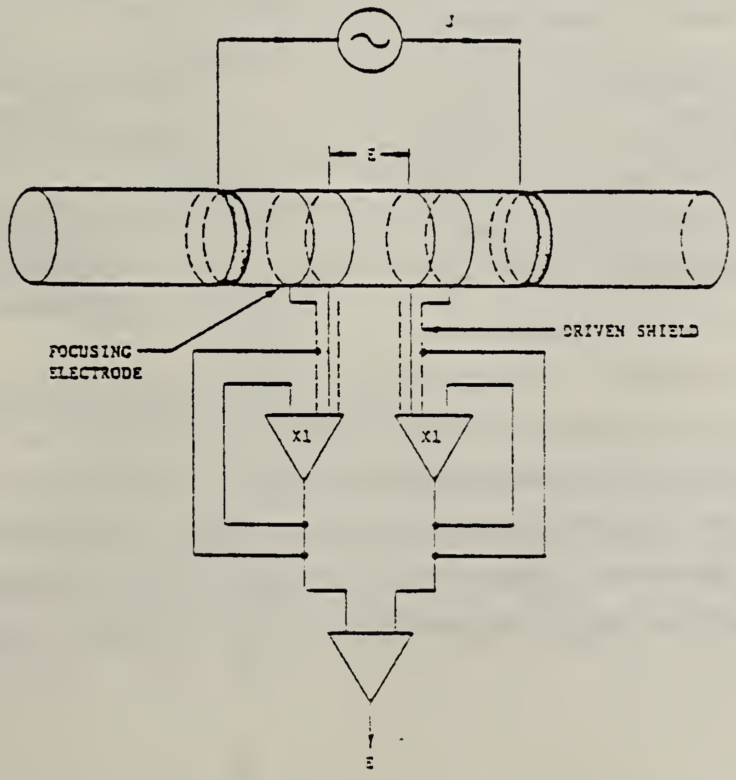

FIGURE 14. SCHEMATIC OF A TYPICAL FOUR-ELECTRODE SAMPLE HOLDER (SEE FIGURES 12 AND 13).

entered the sample, by which time the DC electrical conductivity has increased by an order of magnitude (see detailed discussions in [12]. The dielectric properties do not change in the first monolayer as the strongly bound water molecules are strongly hindered from rotating, hence the orientational polarization is reduced, with the result that the dielectric permittivity of water in the first adsorbed layer is reduced to about 6 from the free water value of 80. By the time a few weight percent water has entered the sample, the dielectric permittivity has increased (typically) by several tens of percent at low frequencies and not at all at high frequencies, while the DC electrical conductivity has increased by as many as 9 orders of magnitude.

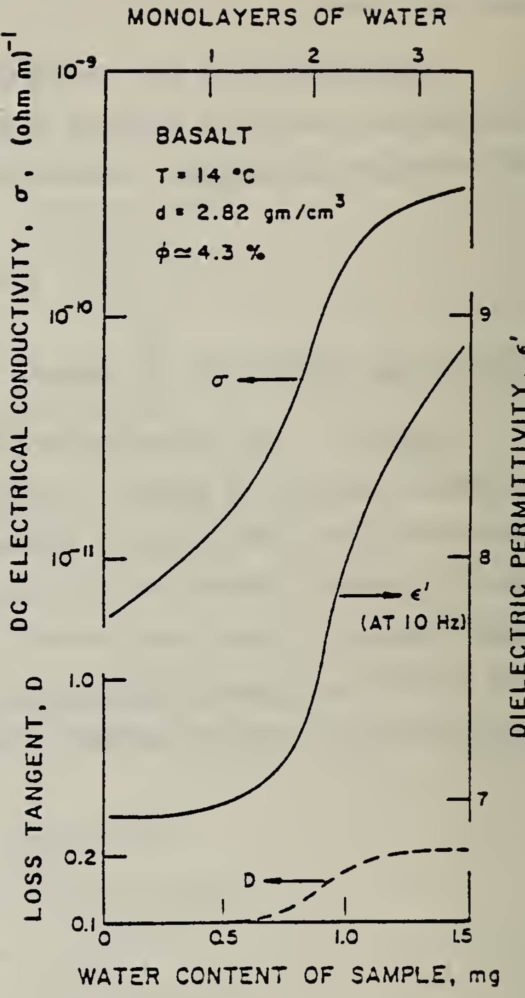

FIGURE 15. VARIATION OF ELECTRICAL PROPERTIES OF BASALT, PARTIALLY SATURATED WITH WATER.

The frequency dependence of wet and dry rocks is generally well understood, but not widely measured on many rock types. The pore structure and water-rock chemical interactions are the dominant causes of frequency dependence. The nonlinear (current/voltage) dependence of electrical properties are only minimally understood for iron sulfide systems, and little measured or understood for others. The pressure dependence of electrical properties is generally unimportant except in wet rocks as pressure causes porosity changes, as it affects the liquid-gas phase of water, and above the critical temperature of water. Pressure has very little effect on the electrical properties of dry rocks.

ELECTRICAL PROPERTIES OF GRANITE

Figure 16 illustrates a summary of the available data for the electrical properties of granite as a function of temperature, water content, and pressure (a similar figure holds for basalt; see [16]). Lebedev and Khitarov [11] and Hyndman and Hyndman [7] have previously discussed the importance of water on electrical properties deep within the earth (see also [2,3,4,6]). To incorporate recent results, the next few figures quickly review the effects of pressure, temperature, and salt concentration upon water in rocks (see also [16,19]).

First, water has two striking effects as shown in Figure 6. The amplitude of the resistivity changes by many orders of magnitude as water is added to granite, and the temperature dependence changes nearly as dramatically. Near room temperature the activation energy of the electrical resistivity of dry granite is around 0.5 eV, increasing to about 1.5 eV near a few hundred degrees Celsius. The activation energies in wet granite are near 0.1 eV and very constant with increasing temperature (until the melting temperature of the granite or the critical temperature of the solution is reached.

At 1000°C, in order to produce a one order of magnitude change in electrical resistivity of a dry granite, either the oxygen fugacity must be changed by more than 6 orders of magnitude, or the dry hydrostatic pressure by 1300 MPa, or the temperature by 55°C, or the water content by 0.3 weight percent. At lower temperatures, the effects of water are even more pronounced and dominant. From room temperature to melting, the electrical resistivity of granite is mostly controlled by water content and temperature, relatively independent of either lithostatic or hydrostatic pressure.

ELECTRICAL PROPERTIES OF SHALE AND TUFF

A preliminary search of the literature provided little information on the electrical properties of shale and tuff other than some room temperature DC conductivity as well as relative dielectric permittivity and loss tangent which are reported here in Tables 1 and 2. New measurements on tuff will be forthcoming soon, however.

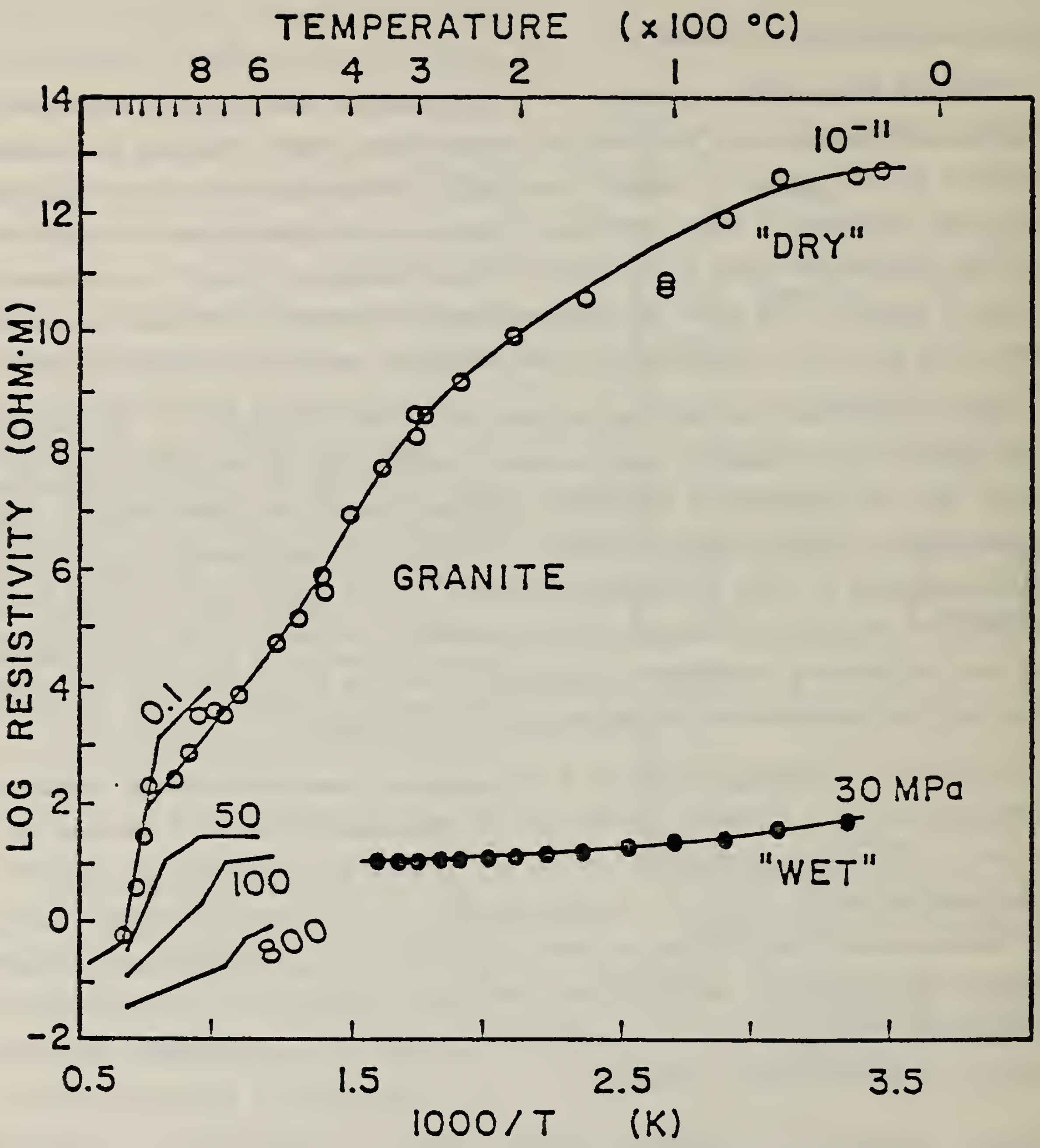

FIGURE 16. SUMMARY OF THE AVAILABLE DATA ON ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR WET AND DRY GRANITE.

Open circles are vacuum dry (10^{-11} MPa) Westerly Granite (using the experimental techniques described in [21-23]). Closed circles are 0.4 molar $NaCl_{aq}$ solution-saturated Westerly Granite (using the experimental techniques described in [19]). Solid lined (with water pressure indicated in MPa) are water-saturated El'dzurta Granite from the Northern Caucasus [11].

TABLE 1. DENSITY, DC ELECTRICAL CONDUCTIVITY, RELATIVE DIELECTRIC PERMITTIVITY AND LOSS TANGENT OF BASALT, GRANITE, SHALE, AND TUFF

Name/Description[1]	Density	DC Cond.	Relative Dielectric Permittivity & Loss Tangent							
	gm/cc	Mho/m	1 kHz		10 kHz		100 kHz		1 MHz	
Basalt Hornblende [7.5] Chaffee, CO	2.635	9.9E-09	48.1	0.7061	22.4	0.4890	14.6	0.2843	10.8	0.1973
Basalt Amygdaloidal [246.6] MI	3.134	2.4E-10	24.5	0.2026	17.9	0.1843	14.7	0.1161	13.1	0.0737
Basalt Flood [58.5] U.S.B.M.	2.843	1.4E-09	29.0	0.3533	21.1	0.1851	17.7	0.1133	15.5	0.1004
Basalt [166.6A] HI	2.365	6.0E-10	8.5	0.0833	8.0	0.0392	7.7	0.0183	7.4	
Basalt [168.6D] HI	2.365	5.2E-10	7.9	0.0791	7.5	0.0368	7.2	0.0185	6.9	
Basalt [166.6] HI	2.365	7.9E-10	8.4	0.1117	7.9	0.0438	7.5	0.0229	7.5	0.0126
Basalt [5.5] Chaffee, CO	1.953	7.3E-09	29.3	0.5480	16.8	0.3763	11.1	0.2762	8.0	0.2136
Basalt [R604] HI	2.136	1.7E-11	10.1	0.0494	9.6	0.0325	9.2	0.0327	8.8	0.0441
Basalt [R606] HI	2.230	1.5E-11	10.7	0.0277	10.4	0.0190	10.1	0.0238	9.8	0.0487
Basalt [R607] HI	2.184	1.3E-11	10.3	0.0266	10.1	0.0185	9.8	0.0210	9.5	0.0409
Basalt [R608] HI	2.029	1.2E-11	9.9	0.0349	9.5	0.0212	9.3	0.0233	9.0	0.0404
Basalt [R609] HI	2.048	6.4E-12	8.1	0.0263	7.8	0.0196	7.6	0.0180	7.5	0.0235
Basalt [R610] HI	2.043	4.5E-12	7.7	0.0238	7.5	0.0137	7.4	0.0127	7.3	0.0194
Basalt [R611] HI	1.630	1.0E-11	6.3	0.0255	6.1	0.0146	6.0	0.0134	5.9	0.0177
Basalt [R612] HI	2.462	1.2E-09	12.9	0.2762	10.3	0.1208	9.3	0.0624	8.7	0.0522
Basalt [R613] HI	2.617	2.7E-11	13.2	0.0397	12.7	0.0246	12.3	0.0254	11.9	0.0385
Basalt [R614] HI	2.807	2.3E-11	10.7	0.0793	9.8	0.0532	9.2	0.0415	8.7	0.0374
Basalt [R615] HI	2.817	1.4E-11	11.4	0.0514	10.8	0.0350	10.3	0.0362	9.8	0.0482
Basalt [R616] HI	2.882	1.2E-11	10.9	0.0336	10.6	0.0224	10.2	0.0260	9.8	0.0399
Basalt [R617] HI	2.105	1.2E-11	7.0	0.0880	6.4	0.0545	6.0	0.0374	5.8	0.0241
Basalt [R618] HI	1.979	7.8E-12	9.2	0.0370	8.8	0.0215	8.6	0.0202	8.4	0.0315
Basalt [R619] HI	1.949	2.9E-13	7.1	0.0291	6.8	0.0180	6.7	0.0184	6.5	0.0278
Basalt [R620] HI	2.402	1.4E-11	10.9	0.0334	10.5	0.0212	10.3	0.0226	9.9	0.0357
Basalt [R621] HI	2.384	7.5E-12	8.0	0.0597	7.5	0.0354	7.2	0.0255	7.0	0.0223
Basalt [R622] HI	2.611	2.4E-09	12.0	0.1487	10.5	0.0796	9.6	0.0564	8.9	0.0534
Basalt [R623] HI	2.490	5.2E-11	9.7	0.0648	9.1	0.0349	8.8	0.0299	8.4	0.0351
Basalt [R624] HI	2.693	1.5E-11	10.0	0.0471	9.5	0.0350	9.1	0.0342	8.7	0.0381
Basalt [R625] HI	2.919	4.9E-10	15.0	0.2381	12.2	0.1164	10.9	0.0715	10.1	0.0596

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[1] For explanation of bracketed numbers see footnote at end of table.

TABLE 1. DENSITY, DC ELECTRICAL CONDUCTIVITY, RELATIVE DIELECTRIC PERMITTIVITY AND LOSS TANGENT OF BASALT, GRANITE, SHALE, AND TUFF (continued)

Name/Description	Density	DC Cond.	Relative Dielectric Permittivity & Loss Tangent							
	gm/cc	Mho/m	1 kHz		10 kHz		100 kHz		1 MHz	
Basalt [R626] HI	2.886	2.2E-11	12.6	0.0780	11.5	0.0574	10.6	0.0607	9.7	0.0783
Basalt [R628] HI	1.414	1.7E-11	5.5	0.0582	5.1	0.0387	4.9	0.0307	4.7	0.0302
Basalt [R629] HI	1.649	1.3E-11	7.2	0.0286	7.0	0.0167	6.8	0.0195	6.6	0.0296
Basalt [R630] HI	2.012	1.1E-11	9.6	0.0328	9.3	0.0181	9.1	0.0172	9.0	0.0317
Basalt [R631] HI	2.595	2.4E-11	15.1	0.0321	14.7	0.0186	14.4	0.0185	14.1	0.0408
Basalt [R632] HI	2.527	1.6E-11	12.1	0.0188	11.9	0.0161	11.6	0.0272	11.0	0.0629
Basalt [R802-A] HI	1.612	2.9E-11	7.0	0.0395	6.7	0.0236	6.5	0.0215	6.4	0.0285
Basalt [R802-B] HI	0.767	5.7E-12	3.3	0.0205	3.2	0.0148	3.2	0.0165	3.1	0.0212
Basalt [R802-C] HI	0.814	4.7E-12	3.5	0.0258	3.4	0.0140	3.4	0.0149	3.3	0.0227
Basalt [R802-X-1] HI	1.932	4.8E-12	7.5	0.0335	7.3	0.0192	7.1	0.0187	7.0	0.0297
Basalt [R802-X-2] HI	1.775	6.7E-12	6.7	0.0274	6.5	0.0179	6.4	0.0191	6.2	0.0310
Basalt [R802-X-3] HI	1.454	2.2E-11	5.6	0.0330	5.4	0.0179	5.3	0.0183	5.1	0.0307
Basalt [R803-A-1] HI	1.624	2.9E-11	6.8	0.0369	6.6	0.0241	6.4	0.0223	6.2	0.0325
Basalt [R803-A-2] HI	1.319	1.3E-11	5.3	0.0301	5.2	0.0187	5.0	0.0173	5.0	0.0222
Basalt [R803-A-3] HI	1.038	1.3E-11	4.5	0.0361	4.3	0.0192	4.2	0.0186	4.1	0.0234
Basalt [R804-1] HI	1.048	6.8E-12	4.4	0.0208	4.3	0.0171	4.2	0.0101	4.1	0.0206
Basalt [R804-2] HI	0.928	2.8E-12	3.4	0.0135	3.3	0.0110	3.3	0.0112	3.3	0.0127
Basalt [R805-1] HI	0.837	7.8E-12	3.9	0.0294	3.8	0.0163	3.7	0.0148	3.7	0.0244
Basalt [R805-2] HI	0.876	1.6E-11	4.0	0.0285	3.9	0.0152	3.8	0.0143	3.8	0.0230
Basalt [R806-1] HI	0.769	4.0E-12	3.4	0.0135	3.3	0.0145	3.3	0.0134	3.2	0.0121
Basalt [R807-A] HI	0.844	2.5E-12	3.9	0.0351	3.8	0.0194	3.7	0.0149	3.6	0.0188
Basalt [R807-B] HI	0.853	3.0E-11	4.3	0.0430	4.1	0.0213	4.0	0.0166	3.9	0.0221
Basalt [R808-A] HI	0.802	4.1E-12	3.1	0.0292	3.0	0.0196	3.0	0.0201	2.9	0.0214
Basalt [R808-B] HI	0.837	4.6E-12	3.3	0.0341	3.2	0.0198	3.1	0.0204	3.1	0.0224
Basalt [R815] HI	2.925	1.0E-09	15.4	0.2114	12.9	0.1051	11.5	0.0721	10.6	0.0631
Basalt [R816] HI	2.874	1.5E-11	15.6	0.0420	14.7	0.0503	13.5	0.0642	12.2	0.0773
Basalt [R818] HI	3.039	3.0E-12	9.3	0.0191	9.0	0.0189	8.8	0.0214	8.6	0.0275
Basalt [R819] HI	3.019	8.3E-08	18.0	0.1196	16.6	0.0677	15.1	0.0708	13.7	0.0738

TABLE 1. DENSITY, DC ELECTRICAL CONDUCTIVITY, RELATIVE DIELECTRIC PERMITTIVITY AND LOSS TANGENT OF BASALT, GRANITE, SHALE, AND TUFF (continued)

Name/Description	Density	DC Cond.	Relative Dielectric Permittivity & Loss Tangent							
	gm/cc	Mho/m	1 kHz		10 kHz		100 kHz		1 MHz	
Basalt [R821-A] HI	2.545	2.7E-11	10.4	0.0321	10.0	0.0224	9.7	0.0254	9.4	0.0386
Basalt [R821-B] HI	2.614	3.3E-11	11.6	0.0403	11.1	0.0293	10.6	0.0324	10.1	0.0467
Basalt [R822-A] HI	2.914	1.0E-11	10.2	0.0131	10.0	0.0115	9.8	0.0124	9.7	0.0187
Basalt [R822-B] HI	2.863	9.3E-12	10.2	0.0131	10.0	0.0116	9.8	0.0134	9.7	0.0204
Basalt [R823-B] HI	2.255	2.6E-11	9.1	0.0362	8.7	0.0243	8.4	0.0264	8.1	0.0385
Beryl [180.6] ME	2.644	2.8E-13	7.6		7.3	0.0231	7.0	0.0316	6.8	0.0316
Biotite Gneiss [308.6] CO	2.660	3.7E-12	6.1	0.0663	5.6	0.0433	5.4	0.0226	5.1	
Bornite [18KCC] Butte, MT	3.269	6.2E-12	9.2	0.1147	7.7	0.1084	6.7	0.0806	6.2	0.0504
Breccia Andesitic [88.6] Ouray, CO	2.507	1.8E-10	7.8	0.0955	7.1	0.0552	6.7	0.0336	6.5	0.0179
Breccia Basalt [95.6] Lane, OR	2.450	1.1E-07	108.5	0.7248	52.4	0.5205	31.2	0.3548	21.0	0.2844
Granite Aplite [65.6] Boulder, CO	2.573	2.3E-12	6.0	0.0113	5.7	0.0249	5.6	0.0208	5.5	0.0137
Granite Biotite [76.6] RI	2.591	3.7E-11	8.1	0.1354	6.9	0.0835	6.4	0.0494	6.1	0.0292
Granite Westerly	2.650	9.0E-12	6.9	0.0672	6.2	0.0589	5.8	0.0373	5.6	0.0182
Granite Westerly A	2.650	3.0E-11	7.5	0.0753	6.7	0.0596	6.3	0.0347	6.1	0.0196
Granite Westerly B	2.650	1.5E-11	7.6	0.0740	6.9	0.0583	6.4	0.0361	6.3	0.0157
Granite Westerly C	2.650	8.8E-12	7.0	0.0705	6.3	0.0546	5.9	0.0357	5.7	0.0184
Granite Westerly D	2.650	5.0E-12	6.8	0.0620	6.2	0.0546	5.8	0.0325	5.5	
Granite Biotite [70.6] Pikes Peak, CO	2.616	1.2E-11	8.8	0.1066	7.6	0.0853	6.9	0.0645	6.4	0.0479
Granite [150.6] Rockport, MA	2.606	2.3E-11	6.7	0.1159	5.9	0.0595	5.6	0.0314	5.2	
Granite [244.0] GA	2.662	3.3E-11	8.9	0.1097	7.7	0.0807	7.1	0.0390	6.6	
Granite [245.6] HI	2.577	4.4E-12	6.1	0.0265	5.9	0.0193	5.7	0.0198	5.6	0.0144
Shale Arenaceous [387.6] CO	2.223	9.9E-10	10.6	0.3144	7.8	0.1899	6.4	0.1259	5.6	0.0929
Shale Argillaceous [386.6] CO	2.289	2.3E-07	1923.3	0.3245	693.6	0.9845	206.1	0.8227	89.9	0.7354
Shale Calcareous [383.6] CO	2.497	6.7E-08	42.3	1.3025	19.3	0.6224	12.5	0.2948	9.7	0.1563
Shale Phosphatic [384.6] NY	2.510	3.3E-11	8.5	0.0154	8.2	0.0112	8.0	0.0114	8.2	0.0032
Shale Black [385.6] SD	2.460	1.0E-09	16.3	0.2394	12.4	0.1703	10.1	0.1391	8.4	0.1209
Shale Illite Bearing [449.6] NY	2.506	2.2E-08	2.49	0.4831	17.1	0.2544	13.1	0.1726	10.6	0.1547

TABLE 1. DENSITY, DC ELECTRICAL CONDUCTIVITY, RELATIVE DIELECTRIC PERMITTIVITY AND LOSS TANGENT OF BASALT, GRANITE, SHALE, AND TUFF (continued)

Name/Description	Density	DC Cond.	Relative Dielectric Permittivity & Loss Tangent							
			1 kHz		10 kHz		100 kHz		1 MHz	
	gm/cc	Mho/m								
Tuff Lapilli [90.6] CA	2.038	1.9E-09	74.3	0.3204	33.7	0.5344	18.4	0.3885	12.2	0.2851
Tuff Rhyolite [87.6] Ennis, MT	1.849	4.9E-09	5.3	0.4186	4.1	0.1337	3.8	0.0370	3.8	0.0020
Tuff Green Lapilli [89.6] Butte, MT	2.140	5.5E-08	58.1	1.0568	23.8	0.6530	14.1	0.3664	9.9	0.2351
Tuff White Lapilli [91.6] Butte, MT	1.800	1.0E-08	35.1	0.7280	16.3	0.4477	11.9	0.2932	8.5	0.2163
Tuff [62.5] U.S.B.M.	0.931	4.6E-11	3.5	0.0500	3.3	0.0485	3.0	0.0638	2.7	0.0645
Tuff [94.6] CO	2.413	1.3E-10	8.4	0.1123	7.5	0.0723	6.9	0.0534	6.5	0.0411

TABLE 2. DENSITY, DC ELECTRICAL CONDUCTIVITY, RELATIVE DIELECTRIC PERMITTIVITY AND LOSS TANGENT OF BASALT, GRANITE, AND SHALE OUTSIDE THE USA

Name/Description	Density	DC Cond.	Relative Dielectric Permittivity & Loss Tangent							
			1 kHz		10 kHz		100 kHz		1 MHz	
	gm/cc	Mho/m								
Basalt Thingvellir, Iceland	2.916	8.4E-11	10.4	0.0444	9.9	0.0297	9.6	0.0209	9.4	0.0213
Basalt [6.5] Germany	3.030	5.8E-09	37.6	0.8048	19.6	0.4278	14.2	0.2020	11.6	0.1220
Granite Porphyry [162.6] Ontario	2.676	3.6E-12	7.4	0.0424	7.0	0.0350	6.6	0.0381	5.9	
Shale Carbonaceous [388.6] South Africa	2.358	1.1E-11	9.6	0.1033	8.5	0.0726	7.8	0.0544	7.3	0.0388

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[1] Samples without bracketed numbers are from the USGS Petrophysics Laboratory sample collection. Those with bracketed numbers beginning with "R" are from Robertson and Peck [33]. Those with bracketed numbers ending in "KCC" are from G. R. Olhoeft's personal sample collection. Those with other bracketed numbers are from Hunt and Salisbury [34] and references therein. All samples are currently in the possession of G. R. Olhoeft.

REFERENCES

1. Biegler, T., Rand, D.A.J., and Woods, R., "Oxygen Reduction on Sulfide Minerals," in *Trends in Electrochemistry* (Bockris, J.O.M., Editor), Plenum Publishing Corp., New York, NY, 291-302, 1977.
2. Brace, W.F., "Resistivity of Saturated Crustal Rocks to 40 km Based Upon Laboratory Measurements", *The Structure and Physical Properties of the Earth's Crust*, (Heacock, J.G., Editor), AGU Mono. 14, Washington, DC, 243-55, 1971.
3. Brace, W.F. and Orange, A.S., "Further Studies of the Effects of Pressure on Electrical Resistivity of Rocks", J. Geophys. Res., 73, 5407-20, 1968.
4. Burnham, C.W., "Water and Magmas: A Mixing Model", Geochim. Cosmochim. Acta, 39, 1077-84, 1975.
5. Hall, S.H., "A Method of Measuring Rock Electrode Kinetics," J. Electroanal. Chem., 59, 323-33, 1975.
6. Hermance, J.F., "An Electrical Model for the Sub-Icelandic Crust", Geophysics, 38, 3-13, 1973.
7. Hyndman, R.D. and Hyndman, D.W., "Water Saturation and High Electrical Conductivity in the Lower Continental Crust", Earth Planet. Sci. Letrs., 4, 427-32, 1968.
8. Katsube, T.J., Ahrens, R.H., and Collett, L., "Electrical Nonlinear Phenomena in Rocks," Geophys., 38, 106-24, 1973.
9. Klein, J.D. and Shuey, R.T., "Nonlinear Impedance of Mineral-Electrolyte Interface. Part I: Pyrite," Geophysics, 43, 1222-34, 1978.
10. Klein, J.D. and Shuey, R.T., "Nonlinear Impedance of Mineral-Electrolyte Interface. Part II: Galena, Chalcopyrite, and Graphite," Geophysics, 43, 1235-49, 1978.
11. Lebedev, E.B. and Khitarov, N.I., "Dependence of the Beginning of Melting of Granite and the Electrical Conductivity of its Melt on High Water Vapor Pressure", Geochemistry Int., 1, 193-7, 1964.
12. Olhoeft, G.R., "The Electrical Properties of Permafrost," Univ. of Toronto, Toronto, Canada, Ph.D. Thesis, 172 pp., 1975.
13. Olhoeft, G.R., "Electrical Properties," in Initial Report of the Petrophysics Laboratory, U.S. Geological Survey Circular 789, Reston, VA, 1-24, 1979.
14. Olhoeft, G.R., "Nonlinear Electrical Properties," in *Nonlinear Behavior of Molecules, Atoms and Ions in Electric, Magnetic or Electromagnetic Fields* (Neel, L., Editor), Elsevier Publishing Co., Amsterdam, 395-410, 1979.
15. Olhoeft, G.R., "Initial Report of the Petrophysics Laboratory: 1977-1979 Addendum," U.S. Geological Survey Open File Report 80-522, 13 pp., 1980.
16. Olhoeft, G.R., "Electrical Properties of Rocks". *Physical Properties of Rocks and Minerals*. Chapt. 9, (Touloukian, W.R., Judd, W.R., and Roy, R.F., Editors), McGraw-Hill Book Co., New York, NY, 1980.

17. Peter, E., "Electrochemistry of Sulfide Minerals," in Trends in Electrochemistry (Bockris, J.O.M., Rand, D.A.J., and Welch, B.J., Editors), Plenum Publishing Corp., New York, NY, 267-90, 1977.

18. Scott, P.D. and Nichol, M.J., "The Kinetics and Mechanisms of the Non-Oxidative Dissolution of Metal Sulfides," in Trends in Electrochemistry, Plenum Publishing Corp., New York, NY, 291-302, 1977.

19. Ucok, H., "Temperature Dependence of the Electrical Resistivity of Aqueous Salt Solutions and Solution-Saturated Rocks", Univ. of Southern California, Ph.D. Thesis, 154 pp., 1979.

20. Von Hippel, A.R., Dielectric Materials and Applications, MIT Press, Cambridge, MA, 438 pp., 1954.

21. Olhoeft, G.R., "Electrical Properties," Initial Report of the Petrophysics Laboratory, USGS Circular 789, 1-25, 1979.

22. Olhoeft, G.R., "Nonlinear Electrical Properties," Nonlinear Behavior of Molecules, Atoms and Ions in Electric, Magnetic or Electromagnetic Fields, (Neel, L., Editor), Elsevier Publishing Co., Amsterdam, 395-410, 1979.

23. Olhoeft, G.R., "Initial Report of the Petrophysics Laboratory: 1977-1979 Addendum," USGS Open File Report 80-522, 9 pp., 4f., 1980.

24. Duba, A., "Are Laboratory Electrical Conductivity Data Relevant to the Earth?" Acta. Geodaet., Geophys. et Montanist. Acad. Sci. Hung., 11, 485-96, 1976.

25. Fyfe, W.S., Price, N.J., and Thompson, A.B., Fluids in the Earth's Crust, Elsevier Publishing Co., Amsterdam, 383 pp., 1978.

26. Lebedev, E.B., "Physical Properties of Magmatic Melts," Physical-chemistry Problems in Hydrothermal and Magmatic Processes," (Tushkin, A.A., Editor), Nauka Press, Moscow, 33-47, 1975.

27. Robertson, J.K. and Wyllie, P.J., "Rock-water systems, With Special Reference to the Water-deficient Region," Am. J. Sci., 271, 252-77, 1971.

28. Shaw, H.R., "Diffusion of H_2O in Granitic Liquids: Part I. Experimental data; Part II. Mass Transfer in Magma Chambers," Geochemical Transport and Kinetics, Hofman, A.W., Giletti, B.J., Yoder, H.S., Jr., and Yund, R.A., Editors), Carnegie Inst. of Wash., Pub. 634, 139-70, 1974.

29. Olhoeft, G.R., Elliot, C., Fuller, B.D., Keller, G.V., Scott, W.J., and Strangway, D.W., "Proposed Standards for the Presentation of Electrical and Electromagnetic Data," (Report of the Subcommittee on Electrical Standards), Soc. Explor. Geophys., Tulsa, OK, 13 pp., 1978.

30. Ucok, H., Olhoeft, G.R., and Ershaghi, I., "Electrical Resistivity of Geothermal Brines," in Symposium on Oilfield Chemistry and Geothermal Brines, Society of Petroleum Engineers, Dallas, TX, SPE 7878, 163-71, 1979.

31. Drury, M.J. and Hyndman, R.D., "The Electrical Resistivity of Oceanic Basalts," J. Geophys. Res., 84, 4537-46, 1979.

32. Parkhomenko, E.I. and Bondarenko, A.T., *Electroconductivity of Rocks at High Pressures and Temperatures*, Nauka Press, Moscow, Russia, 276 pp., 1972.

33. Robertson, E.C. and Peck, D.L., "Thermal Conductivity of Vesicular Basalt from Hawaii," J. Geophys. Res., 79, 4875-4888, 1974.

34. Hunt, G.R. and Salisbury, J.W., "Visible and Near Infrared Spectra of Minerals and Rocks: XII. Metamorphic Rocks", Modern Geology, 5, 219-228, 1976.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

A study on the feasibility of compiling and evaluating selected physical property data on basalt, granite, shale, and tuff has been completed. The data are to be used to design geological waste repositories for radioactive nuclear waste. Sufficient data on the thermodynamic, mechanical, thermophysical, and electrical properties have been identified to exist in the literature to warrant further data evaluative effort. A bibliography of the selected data is given.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Basalt; bibliography; electrical properties; granite; mechanical properties; nuclear waste isolation; shale; thermodynamic properties; thermophysical properties; tuff.

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